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The vortex tube as a mass separation device

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The Vortex Tube

As a Mass Separation Device

by

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John Drennan

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Abstract

The vortex tube is an arrangement of circular flow channels which causes a high velocity gas stream to separate into streams having different static and stagnant temperatures.

It was thought that three molecular characteristics might be important in a mass separation. These are molecular weights, molecular complexity, and the combination of these. Gas pairs of hydrogen, refrigerant-12, argon represent each of the molecular characteristics.

The vortex tube will function as a mass separation device. The separating ability displayed is small.

INTRODUCTION

The object of this research is to determine if the vortex tube would function as a mass separation device. If it would, how well would it function?

Commercially available gases would be employed at room temperature. An attempt was made to employ the uniflow tube.

The vortex tube is an arrangement of circular flow channels which causes a high velocity gas stream to separate into streams having different static (and stagnant) temperatures.

As usually constructed, it consists of a small hole tangentially entering a much larger tube. The larger tube is blanked off here, forcing the gases to travel helically in one direction. Some provision is made to obtain the center gas stream without the peripheral stream. The flow pattern will be discussed later in this Introduction. Figure 2 shows Vortex Tube V, which was used in the final experimentation.

There is a resemblance to a cyclone. Since the conditions of separation in the vortex tube are much different from the cyclone, an analogy will not be drawn.

Georges Joseph Ranque patented a tubular device in 1933 for the creation of streams of hot and cold gases from a higher pressure system.

During the Second World War, Dr. Rudolph Hilsh developed the tube and incorporated it in a small air liquifaction plant for his laboratory at the Physikalischen Institut, Erlangen Universitat, Germany. Shortly after 1945 he published an article popularizing it.

A flurry of interest in the device as a refrigerator died when it was shown to be much less efficient than the present equipment. Several applications were made in the measurement of gas temperatures. The attempted exploitation uncovered several fundamental problems as to just how the energy was distributed. Experimentation and theorization has continued at a diminished but healthy pace.

For more than ten years interest has been slowly growing in the possibility of separations being obtained through the radial forces existent. A brief chronological history shows the following:

A. F. Johnson (F-5) found no separation of air in 1947.

J. E. Corr (IR-1) found no separation of air in 1948.

S. Comasser (P-26) obtained no separation of air or combustion gases using an Orsat analyser and a mass spectrograph, 1951.

Elser and Hock's (F-10) separations of combustion gases were "consistently... although... poorly quantitatively reproducible", 1951.

H. G. Nöller and H. J. Murtz (F-9) were able to separate H_2 and CO_2, obtaining a separation factor, α, of 2.5. They also claim some separation of the natural isotope mixture of argon using very small cold fractions. They have promised further work.

The major characteristics of the flow pattern within the tube have been well established by McGee (P-12), Scheper, Jr. (P-24), Harnett and Eckert (P-41,42), Scheller (T-46), and many others. A description of the flow pattern follows.

Because of the pressure drop existing between the supply or inlet tube and the large or hot tube, turbulent air is delivered near the speed of sound. The inlet tube is mounted tangentially on the hot tube and the juncture is known as the nozzle. The air, on leaving the small tube, follows the wall of the large tube, developing circular flow. The presence of more nozzles improves the shape of the vortex. This flow becomes helical because the blank in the large tube presents infinite resistance, whereas, in the other axial direction, little resistance is encountered. The gas proceeds helically down the tube, losing kinetic energy to the wall and its own heat capacity. To obtain the characteristic pressure balance of the tube, a valve is necessary. Most of the helically flowing gas, which has been growing hotter, exits to the atmosphere. Some of the air, however, is reversed by the valve and flows along the axis of the tube toward the blanked end. This air becomes cold. If a hole is drilled in the center of the blank, this cold air will flow out. This describes a counterflow vortex tube. At a cross-section of the tube, the flow is, very roughly, of several regimes: boundary layer at the wall, irrotational or a free vortex up to, say, one-third of the radius from the wall, then becoming uncharacterizable, and finally becoming rotational or a fixed vortex near and at the center, with an opposite axial component.

The uniflow tube is quite similar except in the way the cold stream is separated. In this tube, the center core of air is intercepted before it reaches the end of the hot tube. All the air travels only in one axial direction. The design comes from Wenig's idea (P-23) that the creation of hot and cold streams occurs immediately upon establishment of circular flow. Nöller and Murtz (F-9) used this design successfully.

THEORY

The idea that the vortex tube might function as a mass separation device probably came from experiences with "centrifugal force", as the gas has a high angular velocity. The expression for centripetal force, F, for constant angular speed, s, is

$$F = \frac{m\, s^2}{r}$$

where m is a small mass under consideration and r is the distance from the axis of that mass. This equation may be converted to a unit volume basis by using the density, ρ, as

$$F = \frac{\rho\, V\, s^2}{r}$$

where V is a small volume associated with the small mass. Consider two unit volumes of gas spinning at the same speed and radius about a common axis. If the unit volumes contain gases of differing densities, then the forces experienced will be different. Carrying this thinking to a smaller scale where the volume is only large enough to contain a molecule, molecules of different mass would also experience different forces. The molecules are not flung to the outside because that motion is resisted by the pressure gradient, which is constant at any radius.

In a gas mixture, the constant resisting force is not exactly equal to the differing centripetal forces. The difference in forces would be expected to separate them. This would happen simply if the unit volumes were in isothermal laminar flow, which is not the case. An expression is needed for the resistances to displacement by turbulence and thermal diffusion. A short but comprehensive survey, "The Theory of Diffusion", has been presented by Mr. R. Byron Bird.[1] It is clear that the problems solved thus far are limited in application because they are simple cases. Messrs. Opfell and Sage have reviewed the topic "Turbulence on Thermal and Material Transport",[2] and show even a smaller number of treatable situations. From the above, it appears that experimentation will continue to have the major role for some time to come.

The situation is not nearly so clouded in the area of heat and momentum transfer now. A short summary of the average distribution theories follows.

The most comprehensive treatment to date is due to Scheller (T-46) in 1955. By using a somewhat perilous

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1 Thomas B. Drew and John W. Hoopes, Jr., Advances in Chemical Engineering, Volume 1, Academic Press, Inc., 1956, New York, pp. 155-239.

2 ibid., pp. 241-282.

crossplot of extrapolated values, he found that the air enters the hot tube by an essentially isentropic expansion. Depending on whether the axial or radial component is larger, an element of gas will move toward the center or toward the valve while spinning rapidly. He took extensive data and proved that viscous stresses are important only at the orifice plate, the center and the walls of the tube, and that the flow is neither one of constant angular velocity or constant angular momentum. Thus energy must be transferred by theories based on differences in static temperatures of the moving gas. He calculated heat transfer coefficients which were similar to that of film condensation; conduction is negligible.

Ranque (F-6), the inventor of the vortex tube, expected

> "The compressed external layers only have a low velocity while the expanded central layers have the greatest part of their energy in kinetic form and rotate at a very high angular velocity. (The central layers are now much colder because of the expansion and the high velocity; J.D.).
>
> It follows that such a distribution of velocities gives rise to considerable friction between one layer and the next, such that if the layers are long enough, an equilibrium will tend to be established in which all the layers acquire the same angular velocity. Therefore there is a centrifugal migration of energy, the central layers giving their velocity to the external layers."

Hilsch's theorization (F-4) is the same as Ranque's, i.e., a free vortex decaying radially.

Kassner and Knoerschild (G-3) assumed that a free vortex was converted into a forced vortex while moving in the axial, not radial direction. They used a turbulent eddy viscosity in their explanation which was a multiple of the laminar viscosity.

> "The distribution of states across the section is assumed to be that of reversible and adiabatic changes of state of the small pockets of gas as they move in and out radially in the turbulent flow, leading to the equation p/ρ^k = a constant." - from Fulton (P-7), p. 479.

Fulton (P-7) continued along the line of Ranque and Hilsch, but added a simplified mathematical analysis and the idea of heat transfer. He conceived kinetic energy was passing outward much faster than a temperature difference could transfer heat inward. von Deemter (F-16) cites an error by Fulton with regard to a turbulent heat flux.

Webster (P-21) postulated an elemental expansion analysis in which each element of gas did work on the preceding element. Ultimately, friction at the tube wall caused the energy to appear as a temperature rise. His data indicated the whole flow was of constant angular velocity. His theory was discredited because expansion work cannot be performed in the system he postulated.

Scheper, Jr. (P-24) envisioned heat transfer alone as the cause of the temperature "separation". His coefficients were not high enough therefore he did not exclude the possibility of other mechanisms acting.

Dornbrand (G-8) developed a two dimensional laminar vortex theory which neglected heat transfer. He recognizes its very limited application. It is interesting because it considers a free and a forced vortex acting near each other.

THE PLAN OF RESEARCH

First, a successful tube would be developed using air, thus allowing exploratory work. The criterion of acceptability would be comparison to other data in the literature. An attempt would be made to make the uni-flow tube workable. If this proved difficult, the conventional counterflow tube would be developed.

Second, the experimental gases would be used in the successful design to determine whether a separation would occur.

It was thought that three molecular characteristics might be important in a separation. These are molecular weights, molecular volume (complexities), and the combination of these. The original intent was to investigate this three variable system by binaries. Each of the gases represent one of the molecular characteristics. Through consideration of cost and physical properties, the following were chosen:

Hydrogen, MW = 2.0, 0.00518 lbm/ft^3 at 70°F, 1 atm.
R-12, MW = 121.0, 0.333 lbm/ft^3 at 74.5°F, 1 atm.
Argon, MW = 40.0, 0.103 lbm/ft^3 at 70°F, 1 atm.

The Plan of the Experiments follows as Table I.

TABLE I

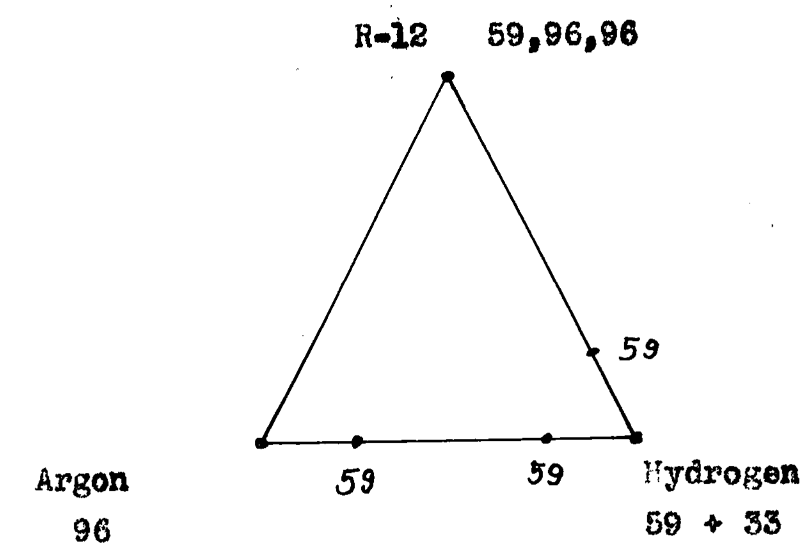
Plan of the Experiments

Gas		R-12	Argon	Hydrogen
Purity		commercial refrigeration	99.95%	99.5-8% dew point: -85°,-97°
Compositions		100	0	
	x	75	25	
of Runs in	x	50	50	
		25	75	
Percent		0	100	
	x	75		25
	x	50		50
		25		75
			75	25
	x		50	50
			25	75
			0	100

Runs were made with each mixture. Each run included operation at 5, 7.5, or 10 atm. inlet pressure. At a pressure level, equilibrium data were taken for various valve settings.

When some experience had been gained with the system, it was decided to eliminate the runs with high concentrations of R-12. Further, the 50-50 runs were omitted, since comparison of 75-25 and 25-75 runs would produce almost as much information. The column of x's above indicates the runs omitted.

Ternary Diagram showing Runs actually performed.



Gauge pressures at which runs were performed are shown outside of the diagram at composition points.

DEVELOPMENT OF THE DESIGN

This occurred in two stages. The first included development of optimum dimensions and characteristics, and attempts at constructing uniflow tubes. The second stage included improving techniques of fabrication.

The literature was searched for dimensions and operating characteristics of tubes; these were compiled and examined. Generally, incomplete data were found on tubes ranging from 4.4 mm. to 3" in hot tube diameter. A graph was made having the gas rate in lb. moles per hour as the abcissa. The ordinates were the squares of the ratios D_o/D_t and D_n/D_t, i.e., the area ratios of orifice to hot tube and nozzles to hot tube. It was hoped that these area vs. flow plots would show a trend, or at least some grouping. About the only thing common to the tubes was that the gas rates were within a factor of 4 of each other. The wide dislocation of the various "optimum" tubes was not encouraging.

Because a number of successful tubes employed these ratios, the following were chosen: $(D_o/D_t)^2 = 0.20 - 0.25$ and $(D_n/D_t)^2 = 0.06$ with $P_n > 105$ psig. Much of this could have been avoided had Dornbrand's paper (G-8) been available earlier. The conclusions above are confirmed by his findings. It is interesting to note one of

TABLE II

Specifications of Vortex Tubes

Tube	D_t	D_o	D_n	L_h	L_c	$(D_o/D_t)^2$	$(D_n/D_t)^2$	Gas Rate	Comments
	inches			D_t units				SCFM	
I	3/4	1/4	1/16	17/3	16/3	.111	.007	nozzle blocked	brass, soldered, uniflow
II	3/4	1/4	1/32	17/3	16/3	.111	.004	not measured	brass, soldered, uniflow
III	3/4	23/64	2x1/8 sq.	32.	32.	.23	.0708	35.	lucite, welded, counter-flow
IV	1/4	1/8	2x3/64 sq. 2x(4/64)	40.	4.	.25	.0896 (.159)	9.	lucite, welded, counter-flow
V	1/4	1/8	2x3/64	40.	1.	.25	.0896	4. to 9.	brass, screwed, counter-flow

VT Tube IV was finished (larger) than designed.

Dornbrand's tubes. His 5 lb. per minute tube achieved a maximum ΔT_c of 56°C while Vortex Tube V achieved a maximum ΔT_c of 38°C in Fig. 3 at 0.6 lb. per min.

As an example of how this was applied to the design of a tube, the computations of Vortex Tube III are presented. The plastic tube had a nominal inside diameter of 3/4". The limits of the $(D_o/D_t)^2$ ratio chosen yield an orifice diameter range of 0.336 to 0.375". The drill size chosen was 23/64". Similarly, the nozzle diameter would be 0.184". However, it was desired to have two nozzles. The choice here is somewhat arbitrary, but the nearest total equivalent area was chosen. Because of the difficulty of machining circular shapes in the tube at this point, square flow channels were necessary. The side of the square would be 0.1156". The closest practical size was 1/8", giving a $(D_n/D_t)^2$ of 0.0708. The literature indicated that the gas rate would be 15 SCFM. When placed in operation, the tube had more capacity than the 35 SCFM Joy compressor. A balance was struck between the compressor and the expansion tube between 56 and 60 PSIG.

The tube design history follows. The uniflow tube was attempted because it should be more efficient and for the novelty. Solder obstructed the nozzle of the first tube and it is possible that the tangentially drilled hole passed the tangent point in both tubes. Because the second tube gave some indication of running "backward", it was decided to switch to the counterflow design. The third tube incorporated a number of improvements, these being use of the diameter ratios, lucite for observation, solvent welding, two nozzles, and a much superior plenum. This last item was suggested by John F. Mahoney. It also included the best nozzle design, a split short spiral found by Martynovski and Alekseev (F-8). Vortex Tube III was quite successful, producing 29° and -17°C simultaneously at 60 PSIG. Unfortunately, it consumed more air than the Joy machine could compress. Tube IV was a scaled-down version of the same design. As in Tube III, the nozzles were hand-contoured with a small power tool. Dental burrs which were nearly 3/64 inch in diameter were used on the later tube, but lack of good control brought the nozzle cross-section to nearly 4/64. Tube IV performed as well as Tube III, yielding 56° and -6°C simultaneously, and consumed 9 SCFM at 97 PSIG. The lucite tube failed in the following fashion toward the end of the 90 PSIG run. Because of the increasing heat and slight pressure, the tube wall deformed outward, starting about one-third along the hot tube length. The section became half a circle and half an ellipse. For safety, testing was discontinued.

With the passing of four months, a good design had been achieved. Vortex Tube V was machined from brass (see Fig. 2) and at first employed a lucite connection to the cold cross. This broke a number of times and a brass one was finally substituted. An attempt was made to cut down the heat transferred by using thin Teflon tape between the orifice block and the connection. Eventually all the threaded joints were faced with a refrigeration sealant. A paper gasket between the hot tube and the orifice block failed and was replaced by a sheet metal one. This was thought necessary to assure no leaks about the nozzles; the nozzles were positioned by a set of fixed dimensions.

All data in the Appendix was taken with Vortex Tube V.

DESCRIPTION OF THE APPARATUS

The apparati employed fell into two groupings, corresponding to the stage of the work. The first grouping, used to achieve a satisfactory design, included:

1) Compressor. A Joy machine located in the basement of the Chemistry building and capable of 35 SCFM at 160 PSIG. The cut off was set at 120 PSIG. Joy Mfg. Co. Type K, Model B 352-SB.

2) Dura Gauge 0-160 PSIG.

3) Vortex Tubes.

4) Leeds and Northrup Cat. #8667 Potentiometer. Leeds and Northrup standard (± 1-1/2°F) copper and constantan wire for couples. Centralab standard rotary switch.

The first group was assembled and run in the Unit Operations Laboratory.

The apparatus for the second group consisted of system charging equipment, a compressor, a recycle valve, storage tank, gauges, the vortex tube and tubing, thermocouples and potentiometer, and a thermal conductivity analyser. The flow diagram is Figure 1.

1) System Charging Equipment. When being run on air, the system was charged by opening the valve on the inlet side of the compressor. When run on the experimental gases, a cylinder was connected and the Valve "5" opened until the desired pressure had built up in the storage tank. If two gases were to be run, this was repeated, the storage tank pressures always being less than those of the cylinder.

2) Compressor. This machine was a Worthington type V4A3, Model 1225, Size 22, which normally can produce 12 SCFM at 3000 PSIG. For these operations, the third stage was disconnected. The second stage safety valve blew at 635 PSIG, although usually the tank was raised to 550 PSIG at the highest.

3) Recycle Valve. This was a 1/4" FPT Hoke high-pressure stainless steel bar-stock valve.

4) Storage Tank. This was a wartime stainless steel oxygen tank. It was hydrostatically tested to 610 PSIG and had a computed capacity of 1.23 cu. ft.

5) Gauges. All in PSIG except vacuum units.

0-5000		Compressor Discharge
0-1000	Lonergan GM	Storage tank
0-3000	Heise	Storage tank, 2 lb. subdivisions

0-160	Dura Gauge	Inlet to the vortex tube
0-30	Clapp	Discharge of the vortex tube
0-3000	Asstd.	Two stage cylinder pressure regulators

6) The Vortex Tube. Described under Development of the Design.

7) Tubing. The majority of the tubing was 1/4" OD high pressure copper tubing. The return line from the vortex tube was 3/8" OD tubing. Most of the valves used were Hoke cast steel 1/8" FPT.

8) Thermocouples and Potentiometer. The four couples were made of Leeds and Northrup Standard ($\pm$ 1-1/2^{o}F) copper and constantan wire. A centralab standard rotary switch was used to connect the three variable couples in series with the fourth couple (maintained at 0^{o}C) and the potentiometer. The Leeds and Northrup Cat. #8667 potentiometer was used. The calibrations are Figures 11 and 12.

9) Thermal Conductivity Analyser. This was a Gow-Mac Laboratory Model 210, serial number 4439. It operates on a 1 SCFH stream each of reference and sample gas.

10) Flow Meter. A Fischer and Porter B6-35-10 tube

with a BSVT-64 float was used. The calibration is Figure 16 and was taken from data supplied by the company. Figure 13 shows the air consumption by Vortex Tube V for various inlet pressure and valve settings.

The second group of apparatus was assembled and run in the Graduate Research Laboratory in the west end of the Powerhouse.

METHOD OF OPERATION

I. Startup

a) Gas Charging

See Flow Diagram, Fig. 1.

The cylinder containing the gas to be charged was connected to the line including Valve 5, Valve 6 opened to the tank, and the rest of the system isolated. A small pressure above atmospheric was permitted to develop by opening the pressure regulators and Valve 5. This constituted a low pressure test for leaks in this part of the system. The line to the 0-3000 PSIG Heise Bourdon tube gauge (hereafter referred to as "P_B") was blown. Then the lines to the compressor were blown. The compressor was started (see Compressor, below) and the gases vented from the second stage disengager. The compressor was permitted to develop a vacuum on the inlet side, including the tank. The tank was again isolated and simultaneously the recycle valve opened, preventing the compressor from developing too great a vacuum.

Gas was bled into the storage tank to approximately the pressure which would give a gas mixture total pressure of 250 psi. Because of its nearness, the 0-1000 PSIG Lonergan gauge (hereafter referred to as "P_T") was used. Having obtained this nominal pressure, P_B was used. Then computation was made giving the total pressure to be obtained on adding the second gas. The addition was merely a repeat of part of the above procedure.

b) The Compressor

The second stage discharge valve and the recycle valve were open at the start. The cooling water was turned on and the compressor started. By closing the recycle valve, the compressor would evacuate the system. After a sufficient time, the recycle valve was opened partly and the disengager valve closed. This permitted the system to be purged and yet not overload the compressor.

c) Mixing

The valves were opened to connect the compressor to the rest of the system and circulation commenced. The recycle valve was used to control the system pressure by permitting only a fraction of the compressed gases to go to the storage tank and vortex tube. The system was run for a minimum of ten minutes, which would allow five complete circulations on a total displacement basis. By the time data was being taken at the first valve setting equilibrium, usually quite some time had passed.

II. Normal Operation

a) Valve Setting

Since the 1/8" IPS bronze globe valve used to throttle the hot tube flow had a regulating range of 0 to 1-5/8 revolutions, these became the limits. Experimentation quickly confirmed the expected, that the lowest temperature attained occurred at 15/16 - 1-1/2 turns generally. Other settings were chosen to try to cover the rest of the range. A run would begin with the valve wide open, causing very little gas to pass through the orifice. The valve was progressively tightened after each equilibrium. This plan reached the lower temperatures quickly and then built up to the highest temperature.

By altering the recycle valve setting, the pressure in the exhaust line to the compressor could be altered. This valve was set so that the pressure in the line was just about atmospheric, thus preventing leaks in the exhaust system.

b) Equilibrium

The test was taking all the temperatures and then taking them at least once again. Only if there was no change would the data be recorded. On runs involving analyses, the same procedure was used after the temperatures had stabilized.

c) Gas Analyses

The instructions for operating the gas thermal conductivity analyser provided by the manufacturer were followed. Briefly, they consist of zeroing the scale, setting the flow rates and current, setting the end of the scale, and reading the meter deflection when a gas sample is passing through. This data was not used.

A qualitative procedure was used later. It consists of setting the high pressure stream reading near the mid-point of the scale and noting deflections when gas samples are passed through. The deflections would be positive or negative depending on which discharge stream were analysed.

All analyses were performed on a continuous basis, i.e., the sample gas was a fraction of the particular discharge stream. The sample was taken at 1 SCFH from a minimum of 4 SCFM.

DISCUSSION

The vortex tube will function as a mass separation device. This is shown by the relative deflections of Table III.

TABLE III

Composition	μ	Net Deflection L_c	Net Deflection L_h	psia	Run	μ' gas anal.
25% A, 75% H_2	.88	-1.1	2.1	73.5	pp 65,66	.64
	.36	-1.4	0.3			.18
	.20	-3.3	-0.1			-.03
75% A, 25% H_2	.22	-4.2	0.3	73.5	pp 70,71	.07
	.33	-3.3	3.0			.48
	.41	-4.5	1.0			.22
	.25	-4.0	0.3			.07
25% R-12, 75% H_2	.33	-3.0	2.2	73.5	pp 67,69	.42

Because it is not known whether the meter scale is linear, and what the error may be, no quantitative estimate will be made. It should be noted that the 0 and 100 scale readings associated with the analysis meter reading have no known significance. Nöller and Murtz (F-9) observed separations and reported them as separation factors, i.e.

$$\alpha = \frac{(x/1-x)_{light}}{(x/1-x)_{heavy}}$$

This could not be done with the data on hand. If the scale were linear, a sort of mass balance might be made, where def. is the deflection noted and m is the total mass.

$$def_P \times m = \mu' \times def_C + (m - \mu') \times def_H$$

or

$$\mu' = \frac{def_P - def_H}{def_C - def_H} = \frac{\text{net } def_H}{\text{net } def_H - \text{net} def_C}$$

In general, the correspondence was poor. See Table III.

The use of two plastic tubes enables these observations on the helical flow pattern to be made. As the gas moved down the hot tube, oil traces developed a greater and greater pitch. This amounted to a four or five-fold increase in a tube having an L_h/D_t of 40. The cold air emerging from the orifice into the cold tube had a short, lazy helix. While Vortex Tube III was running, it was noticedthat threads of water advanced down the hot tube at moderate temperatures. Occasional droplets would follow these threads exactly, as if were confined to a path. This suggests that the streams of air emerging from the two nozzles retain their identity and "chase" each other through the helical path. The pitch of these water courses also increased with distance from the nozzles. Additionally, the distance between water traces increased, indicating that the streams were expanding axially.

While operating with the throttle valve of Vortex Tube V shut tight, a high-pitched whistle was heard. If the valve were not quite tight, the whistle was pulsed at more than 2 per second. The sound would begin at high frequency and fall rapidly. These should not be confused with the rushing gas noises made by the vortex tube during normal operation. A steady, high-pitched whistle on closing the valve completely had been reported by other investigators and was heard in the other vortex tubes operated.

The cold gas fraction, μ, has been corrected for the Joule-Thomson effect. This was done because, although the Joule-Thomson effect characterizes a gas flowing through the vortex tube, it is not attributable to the vortex tube itself. An ideal gas could be passed through the tube and a temperature difference obtained even though the expansion coefficient were zero. In other words, the temperature of the gas was corrected for the pressure change before separation. The air runs were not so corrected in order to have a direct comparison to the literature. Figures 4 and 5 for R-12 show that neither the Joule-Thomson effect correction or its omission yields results similar to air. It is assumed that all gases should yield curves similar to air in the main. By observation it was noticed that T_p should be somewhere between the uncorrected and the corrected values. By the cut and try method, it appears that 60% of the difference will produce a satisfactory graph. See Figure 6. Because of the small coefficient of hydrogen, the corrected and uncorrected plots are no different.

Consideration was given to the kinetic energy possessed by the gas when leaving the tube. The relation between the stagnation and static temperature is

$$\frac{T_{stag}}{T_{stat}} = 1 + \frac{k-1}{k}\,(\text{Mach})^2.$$

This correction amounts to several degrees in some cases. However, since an enthalpy balance was traditionally been used to correlate data, the total enthalpy of each stream is desired. When the gas is brought to rest, the kinetic energy can be recovered as a temperature rise. The thermocouples, being stationary, measured the stagnation temperature. Because of the relatively low velocities encountered, a recovery factor of unity was assumed and the measured temperatures used directly. It is interesting to note that H_2 and R-12 had small kinetic energy in all cases.

Heat transfer by conduction within the brass body was considered. If there were no metal faces and gas films, a proportionately great amount of heat could be transferred. However, all surfaces were either covered with a blue refrigeration sealant or coated with oil. Also, paper gaskets were used on joints in the radial planes. Because of this and because the joints formed regions, it is expected that little alteration of the gas stream temperatures occurred. Martynovski and Alekseev (F-8) used an insulated couper tube and energy balance to correlate their results.

Some heat losses at high temperatures are shown by none of the mass fractions approaching unity and some exceeding unity.

Pressure drops were calculated for flows in the high pressure line and the exhaust manifolds. In all cases it was small. The losses were not calculated in all tables because the magnitude changed only slightly.

The thermal conductivity analysis measurements had to be performed at very low sensitivities, e.g. 0.004 on a scale of 100 possible units. Even on this basis, the analyses showed only small changes. In view of the unsatisfactory situation, Dr. Wenzel suggested a qualitative procedure. It consists of setting the high pressure stream reading near the midpoint of the scale. (This could easily be done even with a sensitivity of 100.) If a separation occurred, the hot and cold streams would show deflections from the set point, one higher, the other, lower. This was actually observed and is shown in Table III.

The manufacturer of the analyzer, Gow-Mac Instrument Company, insist that the system be leak-free for reproducible measurements. The unsatisfactory performance of the analyzer certainly could be explained by leaks. Many hours were spent eliminating leaks; the unscotchable leaks were caused by over-generous thread cutting on certain external connections of the vortex tube.

The viscosity, η, of Air, H_2, and A was taken from Figure 17, p. 371 of the 3rd edition of Perry. The viscosity of well superheated gases is not a function of pressure over moderate ranges. Therefore, the values at one atmosphere were used. The viscosity of R-12 at one atmosphere was taken from the same source. The viscosity of R-12 at higher pressures was taken from Makita.[1]

The densities of Air, H_2, and A were calculated by

$$\frac{P(MW)}{ZRT} = \rho$$

Table IV shows that Z = 1.00 for Air, H_2, and A. The specific volumes of R-12 were taken from Figure 14 which is a plot of the data appearing on pp. 261, 262 of Perry, 3rd edition and Thermo. Props. of "Freon-12" of Low Pressures, Kinetic Chemicals, Inc., 1942.

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1 Makita, T., "The Viscosity of Freons Under Pressure", Rev. Phys. Chem. Japan, Volume 24, pp. 74-80, (1954).

The gas designated R-12 is dichlorodifluoromethane and is sold under the name Genetron-12 by the General Chemical Division of the Allied Chemical Corp. The H_2 and A were obtained from Air Products, Inc.

In runs involving pure R-12, several times the fluid was clearly in the liquid region based on properties. However, the performance of the tube was no different than with all gas flow. Therefore, sub-cooled vapor is suspected. The calculations (noted) were performed using extrapolated (sub-cooled) vapor densities.

The Joule-Thomson correction for R-12 was taken directly from a P-H diagram, Figure 15, which is a plot of the data appearing in Perry, 3rd edition, pp. 261, 262. The coefficients for hydrogen was taken from some of Joule and Thomson's work. The coefficients for argon were taken from p. 788 (not p. 789) Roebuck and Osterberg.[2] The data from the Figures on these two pages do not agree. The data employed give larger, conservative values.

Difficulty was encountered in the analyses because R-12 was strongly adsorbed in the silica gel dessicant. In retrospect, this could have been avoided by removing the gel. The gases could have been dried in H_2SO_4, as it is important to be analyzing constant moisture gases.

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2 Roebuck, J. R., and Osterberg, H., "Joule-Thomson Effect in Argon", Phys. Review, Volume 46, pp. 785-90, (1934).

A sulfuric acid bubbler probably would have removed any traces of oil also, although oil is not thought to have been present to any large extent. The possibility of oil arises from the fact that the Worthington machine was still passing oil, having been rebuilt.

The mixed gas compositions were determined by Dalton's Law of partial pressures.

The measured diameters at the thermocouple locations were

"C"	0.5 "
"P"	0.36"
"H"	0.27"

It is not possible to estimate concentrations in the hot and cold gas streams because, of the three independent variables, only mass fraction and inlet concentration are known. Thus an estimate of the separation factor cannot be made.

Appendix

NOMENCLATURE

D	Diameter
f	friction factor of Brown, et al.
k	C_p/C_v
L	length, gas analysis
MW	molecular weight
p	Pressure
R	Universal Gas Constant
r	radius
Re	Reynolds Number
S	volumetric flow rate, ft^3/min.
T	Temperature
V	Specific Volume
u	linear velocity
Z	compressibility factor
η	viscosity
μ	cold gas mass fraction flowing
ρ	density

Subscripts:

B	pertaining to the Heise gauge
C	pertaining to the cold fraction
H	pertaining to the hot fraction
D	pertaining to the discharge
n	pertaining to the vortex tube nozzle(s)
o	pertaining to the vortex tube orifice
t	pertaining to the vortex tube hot tube
P	pertaining to the compressed gas
r	pertaining to the room

The thermocouples themselves are referred to as "C", "H", "P".

APPENDIX

SAMPLE CALCULATIONS

Cold Mass Flow Fraction, μ

An overall heat balance is

$$m\, C_p\, T_p = \mu\, m\, C_p\, T_C + m(1-\mu)\, C_p\, T_H \; .$$

where the specific heat is expected to change little over the temperature range involved. Placing the equation on a 1 lbmass basis and expanding the hot gas term,

$$T_p = \mu\, T_C + T_H - \mu\, T_H$$

$$T_p - T_H = \mu\,(T_C - T_H)$$

$$\mu = \frac{T_p - T_H}{T_C - T_H}$$

Pressure Drop in Tubing

$$R_e = \frac{D\, v\, \rho}{\eta} = \frac{4\, W}{\pi D\, \eta} = 378.8\, \frac{S\, \rho}{D\, \eta}$$

where S = flow rate in ft^3/min

D = diameter in inches

η = viscosity in cp.

ρ = density, lbm/ft^3

"f", the friction factor, was taken from Fig. 125, p. 140, of Brown, et al, Unit Operations.

General:

$$-\Delta P_f = \frac{2 f' \rho L v^2}{D} = \frac{f \rho L v^2}{2 D g_c} = \frac{\text{lbm ft ft}^2}{\text{ft}^3 \text{ ft sec}^2} \frac{1}{g_c}$$

$$v = \frac{W}{\rho A} = \frac{S}{A}$$

$$-\Delta P_f = \frac{f \rho L}{2 D g_c} \left(\frac{W 4}{\rho \pi D^2}\right)^2 = \frac{f L W^2}{\rho D^5} \quad \frac{16}{2 g_c \pi^2}$$

$$S_\rho = W$$

$$-\Delta P_f = \frac{f L S_\rho S p}{D^5 \quad p} \times .001008$$

where $-\Delta P_f$ = pressure drop in PSI

W = flow rate in lbm/min

D = diameter in inches

ρ = density in lbm/ft^3

L = length of flow in inches

p/p = pressure ratio, $(\text{inlet/tube})^{-1}$

GAS FLOWS

All gas flows were corrected for deviations in pressure, molecular weight, and temperature by means of the following formula taken from p. 335 of Dodge.

$$S = S_o \sqrt{\frac{P \; T_o \; M_o}{P \; T \; M}}$$

The subscript "o" indicates the condition of original measurement.

TABLE IV

Compressibility Factors From Reduced Properties

Formulae:

Hydrogen $T_R = \frac{T}{T_C + 8}$ $P_R = \frac{P}{P_C + 8}$

Others $T_R = \frac{T}{T_C}$ $P_R = \frac{P}{P_C}$

Gas	MW	Temp ^oC	P atm	T_R	P_R	Z
H_2	2.016	40	1	7.6	.048	1.00
		40	10	7.6	.48	1.00
A	39.94	40	1	2.074	.0208	1.00
		40	10	2.074	.208	.995
R-12	120.92	40	1	.814	.0253	.98
		40	10	.814	.253	.77
		20	1	.762	.0253	.974
		20	5	.762	.1263	.86
Air	28.97	40	1	2.37	.0269	1.00
		40	10	2.37	.269	1.00

Compressibility factor from Smith (1949), pp. 69, 70.

Critical properties from Dodge, pp. 160, 662, 663.

Pages 41, 42, and 43 have not been used.

RUN 41

DATA TABLE I

COMPOSITION: Air

Valve Setting	T_c °C	T_h °C	T_p °C	T_r °C	μ	P nom. psig	L_c meter readings	L_h	L_p	Notes
0	6.6	25.2	23.7	23.4	.08	58.8				
1/2	-4.3	27.4	23.5		.12					
1	-9.9	32.3	23.5		.21					
1-1/2	-8.0	67.3	22.4		.60					
1-9/16	6.3	83.2	18.5		.84					
1-1/8	-9.3	41.6	18.5		.45					

RUN 42

DATA TABLE I

COMPOSITION: Air

Valve-Setting	T_c °C	T_h °C	T_p °C	T_r °C	μ	P nom. psig	L_c	L_h	L_p meter readings	Notes
0	2.6	26.8	25.0	23	$.07^{4}$	96.6				
1/2	-4.3	29.0	24.5		$.13^{5}$					
1	-11.2	34.5	23.7		.24					
1-1/2	-12.0	61.2	22.4		.53					
1-9/16	2.1	92.6	17.7		.83					
0	-9.3	29.7	21.1		.22	132				P_D = 6.5
1/2	-10.2	29.4	23.7		.15					6.8
1	-9.3	35.3	25.5		.22					7.25
1-7/16	-5.7	78.6	23.0		.66					
1-9/16	3.4	94.0	17.8		.78					
1/4	-3.5	32.0	21.2		$.30^{4}$					

RUNS 41, 42

DATA TABLE II

COMPOSITION: Air MW: 28.97

Valve Setting	T °C	P PSIA	S_{air} scfm	μ Sp	$1/\rho$ 1 atm.	η	D in.	Re	f	L in.	ΔP	P_{corr} PSIA
0	23.7	14.7	4.2		13.5	.018	.311	21,500	.0252	12	.137	14.8
1	23.7	16.5	6.95	.515	13.5	.018	.311	34,800	.0225	12	.335	16.8
1-1/16		20.1	6.5	.482	13.5	.018	.311	32,600	.0229	12	.407	20.5
0	25.2	14.8	4.2		13.27	.018	.311	21,200	.0255	25	.289	15.1
	6.6	14.8	0.0		12.4	.0171	.311			14		14.8
	23.7	73.5	4.2		13.5	.018	.180	35,900	.0224	50	1.57	71.9
1/2	27.4	14.8		.282	13.7	.0182	.311	18,900	.0260	25	.227	15.0
	-4.3	14.8		.037	12.25	.0166	.311	2,710		14		14.8
	23.5	73.5	4.3	.318	13.5	.0180	.180	37,200	.0223	50	1.63	71.9
1	34.5	16.8		.394	14.15	.0184	.311	26,100	.024	25	.456	17.3
	-11.2	16.8		.121	11.9	.0165	.311	8,950	.031	14	.0262	16.8
	23.7	111.0	6.95	.515	13.5	.0180	.180	60,200	.020	50	2.54	108.5
1-7/16	78.6	20.5		.278	17.7	.0200	.311	17,000	.0267	25	.316	20.8
	-5.7	20.5		.142	12.16	.0168	.311	10,300	.0300	14	.0357	20.5
	23.0	146.7	6.5	.482	13.5	.0180	.180	56,400	.0204	50	1.71	145.0

RUN 52

DATA TABLE I

COMPOSITION: Air

Valve-Setting	T_c °C	T_h °C	T_p °C	T_r °C	μ	P nom. psig	L_c meter readings	L_h	L_p	Notes
0	5.0	28.7	26.3	25.0	.10	96.6				P_D = 4.5
3/8	2.6	28.8	26.3		.10					4.6
3/4	-3.2	32.5	27.4		.14					4.6
1-1/4	-6.1	62.3	27.9		.50					4.4
1-19/32	21.0	94.6	28.3	25.6	.90					3.4

RUN 52

DATA TABLE II

COMPOSITION: Air

Valve Setting	T °C	P PSIA	S_{air} scfm	S_{mix} cfm	ρ	η	D in.	Re	f	L in.	ΔP	P_{corr} PSIA
	27.0	19.2	6.95	7.9	.0957	.0182	.311	50,000	.0208	12	.516	19.7
0	28.7	19.7										20.2
	5.0	19.7										19.7
	26.3	111.3										108.8
3/8	28.8	19.8										20.3
	2.6	19.8										19.8
	26.3	111.3										108.8
3/4	32.5	19.8										20.2
	-3.2	19.8										19.9
	27.4	111.3										108.8
1-1/4	62.3	19.6										19.8
	-6.1	19.6										19.7
	27.9	111.3										108.8
1-19/32	94.6	18.6										18.6
	21.0	18.6										18.9
	28.3	111.3										109.

RUN 44

DATA TABLE I

COMPOSITION: 100% Argon

Valve-Setting	T_c °C	T_h °C	T_p °C	T_r °C	μ	P nom. psig	L_c	L_h	L_p	Notes
							meter readings			
0	-3.0	25.2	22.7 (19.3)		.09 (.21)	96				P_D = 1.9
3/8	-9.0	27.2	23.7 (20.3)		.10 (.19)					
15/16	-13.3	32.8	23.7 (20.3)		.20 (.27)					

Parentheses indicate values corrected for Joule-Thomson effect.

RUN 44

DATA TABLE II

COMPOSITION: 100% Argon MW: 39.94

Valve Setting	T ^{o}C	P PSIA	$\frac{S_{air}\ scfm}{S_{mix}\ cfm}$	μ_{Sp}	ρ	η	D in.	Re	f	L in.	ΔP	P_{corr} PSIA
3/8	23.7	16.6	7.6/6.4	.647	.1152	.0222	.311	35,500	.014	12	.211	16.8
0	16.0	25.2		.563	.116	.0221	.311	31,000	.0232	25	.55	17.4
	16.0	-3.0	7.5/6.32	.057	.128	.0205	.311				negl.	16.8
	110.7	22.7		.64	.772	.0224	.180	60,000	.0193	50	2.74	108.0
3/8	16.8	27.2		.584	.1151	.0220	.311	32,400	.0230	25	.59	17.4
	16.8	-9.0	7.6/6.4	.063	.131	.0200	.311					16.8
	110.7	23.7		.647	.77	.0222	.180	61,400	.0199	50	2.88	107.8
15/16	16.8	32.8		.484	.113	.0225	.311				.396	17.2
	16.8	-13.3	7.05/5.94	.119	.1331	.0198	.311					16.8
	110.7	23.7		.603	.77	.0222	.180	56,900	.0204	50	2.58	108.1

RUN 46

DATA TABLE I

COMPOSITION: R-12

Valve-Setting	T_c °C	T_h °C	T_p °C	T_r °C	μ	P nom. psig	L_c meter readings	L_h	L_p	Notes
0	1.6	23.0	25.0 (9.0)	25.9	-.094 (.65)	95.5				
15/16	-4.3	34.0	27.6 (12.4)	26.2	.17 (.56)	95.0				
3/8	-1.5	28.7	26.3 (10.0)	25.8	.08 (.62)	95.0				
1-19/32	13.0	72.1	22.7 (6.1)	25.4	.84 (1.12)	95.0				
0	18.5	24.0	26.8^5 (19.1)	24.8	-.52 (.89)	59				
1-1/16	3.4	28.7	25.8 (18.3)		.12 (.41)	59				
1-19/32	19.9	56.2	19.5 (10.6)	25.0	1.04 (1.26)	59				

Underlined quantities are in two phase region.
Parentheses indicate value corrected for Joule-Thomson effect.

RUN 46

DATA TABLE II

COMPOSITION: R-12

Valve Setting	T °C	P PSIA	$\frac{S_{air}\ scfm}{S_{mix}\ cfm}$	μ Sρ	$\frac{1}{\rho}$	η	D in.	Re	f	L in.	ΔP	P_{corr} PSIA
1-19/32	22.1	16.7	4.65/2.28	.819	2.78	.0122	.311	81,700	.0186	12	.144	16.8
0	23.2	15.1					.311			25	.1	15.2
	1.6	15.1					.311			14	.2	15.3
	25.0	110.2					.180			60	2.9	107.3
15/16	34.1	14.8					.311			25		14.9
	-4.3	14.8					.311			14		15.0
	27.6	109.7					.180			60		107.2
3/8	28.7	14.8					.311			25		15.0
	-1.5	14.8					.311			14		14.9
	26.3	109.7					.180			60		107.2
1-19/32	72.2	14.8					.311			25		14.8
	12.9	14.8					.311			14	.16	15.0
	22.7	109.7					.180			60	1.05	108.6
0	24.0	14.7		.529	3.9	.0124	.311	52,000	.0207	12	.0935	14.8
	24.0	14.8			3.9	.0124	.311			25		14.9
	18.5	14.8	4.2				.311			14		14.9
	26.8	73.7	2.06	.529	.58		.180			60		72.4
1-1/16	28.7	14.8		.609	3.24	.0126	.311	60,700	.0199	25	.22	15.0
	3.4	14.8		.0495	2.93	.0117	.311				negl.	14.8
	25.8	73.7		.659	.57	.0136	.180	101,900	.0178	50	1.313	72.4
1-19/32	56.2	14.8		0	3.58	.0133	.311					14.8
	19.9	14.8	3.7	.58	3.13	.0122	.311	58,000	.0201	14	.1025	14.9
	19.5	73.7	1.81	.58	0.57	.0135	.180	90,000	.0183	50	1.02	72.7

RUN 49

DATA TABLE I

COMPOSITION: R-12

Valve-Setting	T_c °C	T_h °C	T_p °C	T_r °C	μ	P nom. psig	L_c meter readings	L_h	L_p	Notes P_D	T_p less JT effect
0	3.6	20.5	<u>24.5</u>	26.9	-.237 (.66)	96.6				2.75	9.1
1	0	24.0	<u>24.3</u>		.0125 (.62)					2.75	9.1
1-19/32	14.0	62.7	<u>22.1</u>	28.9	.835 (1.1)					2.0	9.1
3/4	1.3	26.2	<u>23.7</u>	27.6	.1002 (.70)					2.8	8.8

Joule-Thomson effect fractions calculated from enthalpies. Parentheses indicate values corrected for Joule-Thomson effect.

Underlining indicates sub-cooled vapor.

RUN 49

DATA TABLE II

COMPOSITION: R-12 MW: 120.92

Valve Setting	T °C	P PSIA	$\frac{S_{air}\ scfm}{S_{mix}\ cfm}$	Sρ	$\frac{1}{\rho}$	η	D in.	Re	f	L in.	ΔP	P_{corr} PSIA
0	24.5	17.5	$\frac{7.5}{3.68}$	1.379	2.67	.0122	.311	137,600	.0168	12	.354	17.8
1-19/32	22.1	16.7	$\frac{4.65}{2.28}$	.819	2.78	.0122	.311	81,700	.0186	12	.144	16.8
0	20.5	17.8		.48	2.57	.0122	.311	48,000	.021	25	.108	17.9
	3.6	17.8	$\frac{7.5}{3.68}$	.93	2.43	.0118	.311	96,200	.0181	14	.185	18.0
	24.5	111.3		1.41	.35	.0148	.180	200,000	.0155	50	2.90	108.4
1	24.0	17.8		.49	2.61	.0124	.311			25		17.9
	0	17.8	$\frac{6.94}{3.4}$	.81	2.40	.0117	.311			14		18.0
	24.3	111.3		1.30	.35	.0147	.180	186,000	.0158	50		108.8
1-19/32	62.7	16.8			3.12	.0134	.311			25		16.8
	14.0	16.8	$\frac{4.65}{2.28}$	.819	2.70	.0120	.311	93,000	.0181	14	.159	17.0
	22.1	111.3		.819	.333	.0153	.180	112,600	.0176	50	1.05	110.3
3/4	26.2	17.8		1.07	2.62	.0125	.311			25		18.0
	1.3	17.8	$\frac{7.5}{3.68}$	.27	2.41	.0117	.311			14		17.9
	23.7	111.3		1.34	.34	.0149	.180			50		108.8

RUN 57

DATA TABLE I

COMPOSITION: H_2

Valve-Setting	T_c °C	T_h °C	T_p °C	T_r °C	μ	P nom. psig	L_c meter	L_h readings	L_p	Notes
0	11.9	25.0	22.7 (25.3)	21.7	.176 (.0229)	32.5				
3/4	8.2	27.0	23.3 (25.9)		.197 (.0585)					
1-1/8	0.5	34.5	23.5⁻ (26.1)		.325 (.247)					
1-19/32	17.2	70.4	23.5⁻ (26.1)		.88 (.838)					

Parenthesis indicate values corrected for Joule-Thomson effect.

RUN 57

DATA TABLE II

COMPOSITION: H_2 MW: 2.016

Valve Setting	T °C	P PSIA	$\frac{S_{air}\ scfm}{S_{mix}\ cfm}$	μ Sρ	ρ	η	D in.	Re	f	L in.	ΔP	P_{corr} PSIA
0	25	14.8		.055	.00512	.0088	.311	7,610	.033	25	.169	15.0
	11.9	14.8	3.41	.0118	.00535	.0086	.311	1,630	.036	14	negl.	14.8
	22.7	47.2	13.0	.067	.0166	.0088	.180	16,030	.027	50	.039	47.2
3/4	27	14.8		.054	.00511	.0088	.311	7,480		25		15.0
	8.2	14.8	3.45	.0133	.00544	.0085	.311	1,860		14		14.8
	23.3	47.2	13.1	.0674	.0166	.0088	.180	16,100		50		47.2
1-1/8	34.5	14.8		.0456	.00498	.0090	.311	6,010		25		14.8
	0.5	14.8	3.43	.0219	.0056	.00835	.311	3,115		14		14.8
	23.5	47.2	13.1	.0675	.0166	.0088	.180	16,150		50		47.2
1-19/32	70.4	14.7		.0070	.00446	.0097	.311	856	.0715	25	negl.	14.7
	17.2	14.7	3.0	.0516	.00526	.0080	.311	7,120	.0333	14	.176	14.9
	23.5	47.2	11.4	.0587	.0166	.0088	.180	14,040	.028	50		47.2

RUN 64

DATA TABLE I

COMPOSITION: H_2

Valve-Setting	T_c °C	T_h °C	T_p °C	T_r °C	μ	P nom. psig	L_c	L_h	L_p	Notes
							meter	readings		
0	17.4	27.4	(26.3)		.113	58.8				P_D = 7.4 psig
3/4	13.5	31.6	(30.5)	23.4	.04					
1-1/8	4.2	40.7	(31.5)		.252					
1-3/8	3.6+	44.7	(32.3)		(.30)					
1-19/32	28.4	97.7	(27.6)		(1.01)					

Parentheses indicate values corrected for Joule-Thomson effect.

RUN 64

DATA TABLE II

COMPOSITION: H_2 MW: 2.016

Valve Setting	T °C	P PSIA	$\frac{S_{air}\ scfm}{S_{mix}\ cfm}$	μ Sp	ρ	η	D in.	Re	f	L in.	ΔP	P_{corr} PSIA
Discharge lead	26.0	22.1		.1164	.0076	.0089	.311	15,950	.027	12	.2	22.3
	31.4	21.8		.095	.0077	.0089	.311			12	.13	21.9
0	27.4	22.3		.1001	.0076	.0089	.311	13,800	.0283	25	.258	22.6
	17.4	22.3	4.2	.0163	.07791	.0087	.311	2,280	.35	14	negl.	22.3
	26.0	73.5	15.3	.1164	.0257	.0089	.180	27,600	.0237	50	3.34	70.2
3/4	31.6	22.8		.097	.00771	.0090	.311			25		23.1
	13.5	22.8	4.3	.0203	.00821	.0087	.311			14		22.8
	30.2	73.5	15.2	.1172	.025	.0090	.180			50		70.2
1-1/8	40.7	23.1		.0864	.00759	.0092	.311					23.3
	4.2	23.1	4.27	.0303	.0086	.0084	.311					23.2
	31.2	73.5	15.1	.1167	.0251	.0090	.180					70.2
1-3/8	44.7	22.4		.0754	.00786	.0093	.311			25		22.6
	3.6	22.4	4.14	.0338	.00854	.0084	.311			14		22.5
	32.0	73.5	14.7	.1092	.0251	.0090	.180			50		70.5
1-19/32	97.7	21.9		.0057	.00611	.0103	.311	674	.095	25	negl.	21.9
	31.4	21.9	3.63	.1008	.00744	.0090	.311	13,630	.0283	14	.19	22.1
	27.3	73.5	12.5	.0951	.0255	.0089	.180	22,500	.025	50	2.38	71.1

RUNS 65, 66

DATA TABLE I

COMPOSITION: 24.6% A, 75.4% H_2

Valve-Setting	T_c °C	T_h °C	T_p °C	T_r °C	μ	P nom. psig	L_c meter readings	L_h	L_p	Notes
0	9.25	28.0	24.7	24.7	.176	58.8				
3/4	1.8	30.7	25.7		.173	58.8				
1-1/8	-6.4	39.2	25.5		.300	58.8				
1-9/16	+9.8	94.2	20.2		.876	58.8				
1-9/16							46.9	50.1	48.0	Special Analysis
1-1/8	-6.4	40.0	23.15		.363	58.8	44.7	46.4	46.1	" "
3/4	1.0	30.4	24.4	26.4	.204	58.8	40.6	43.8	43.9	" "

RUNS 65, 66

DATA TABLE II

COMPOSITION: 24.6% A, 75.4% H_2 MW: 11.37

Valve Setting	T °C	P PSIA	$\frac{S_{air}\ scfm}{S_{mix}\ cfm}$	$\mu S \rho$	ρ	η	D in.	Re	f	L in.	ΔP	P_{corr} PSIA
	25.0	14.7		.192	.029		.311					
	25.0	16.3		.192	.0322	.0122	.311	19,200	.026	12	.124	16.4
0	28.0	16.4		.161	.0318	.0122	.311	16,100	.027	25	.191	16.6
	9.25	16.4	4.2	.0308	.03387		.311			14	negl.	16.4
	25.0	73.5	6.64	.192	.1453	.0122	.180	33,200	.0228	50	1.55	72.0
3/4	30.7	16.2		.165								16.4
	1.8	16.2	4.3	.0318								16.2
	26.0	73.5	6.8	.197								72.0
1-1/8	39.2	16.1		.138								16.3
	-6.4	16.1	4.28	.0573								16.1
	25.8	73.5	67.6	.195								72.0
1-9/16	94.2	15.5		.021	.0246	.0141	.311				negl.	15.4
	9.8	15.5	3.85	.156	.032	.0117	.311	16,270	.027	14	.0995	15.5
	19.9	73.5	6.1	.177	.1471	.0121	.180	30,800	.0232	50	1.32	72.2
1-1/8	40.0											16.3
	-6.4		4.28									16.1
	23.45	73.5										72.0
3/4	30.4											16.4
	1.0		4.3									16.2
	24.7	73.5										72.0

RUNS 67, 68, 69

DATA TABLE I

COMPOSITION: 74.8% H_2, 25.2% R-12

Valve-Setting	T_c °C	T_h °C	T_p °C	T_r °C	μ	P nom. psig	L_c	L_h	L_p	Notes
							meter readings			
0	13.3	24.0	21.8		.206					Special Analysis
3/4	6.0	26.0	21.6		2.2					" "
1-1/8	-1.9	33.1	21.4		.334		49.5	44.3	46.5	" "
1-3/8									51.7	" "

RUNS 67, 68, 69

DATA TABLE II

COMPOSITION: 74.8% H_2, 25.2% P-12 MW: 31.94

Valve Setting	T °C	P PSIA	S_{air} scfm / S_{mix} cfm	μ_{sp}	ρ	η	D in.	Re	f	L in.	ΔP	P_{corr} PSIA
	23.0	14.7		.328	.082	.0097	.311	41,200	.0227	12	.124	14.8
0	24.0	14.8		.310	.0820	.0097	.311			25	.24	15.0
	13.3	14.8	4.2 / 4.0	.0177	.085		.311			14	negl.	14.8
	23.45	73.5		.328	.410	.0097	.180	71,300	.0192	50	1.35	72.1
3/4	26.0	14.8		.29	.0814	.0097						15.0
	6.0	14.8	4.3 / 4.10	.047	.0871							14.8
	23.2	73.5		.337	.410							72.1
1-1/8	33.1	14.8		.237	.0795							15.0
	-1.9	14.8	4.28 / 4.07	.0965	.0899							14.8
	23.0	73.5		.334	.410							72.1

RUNS 70, 71

DATA TABLE I

COMPOSITION: 74.6% A, 25.4% H_2

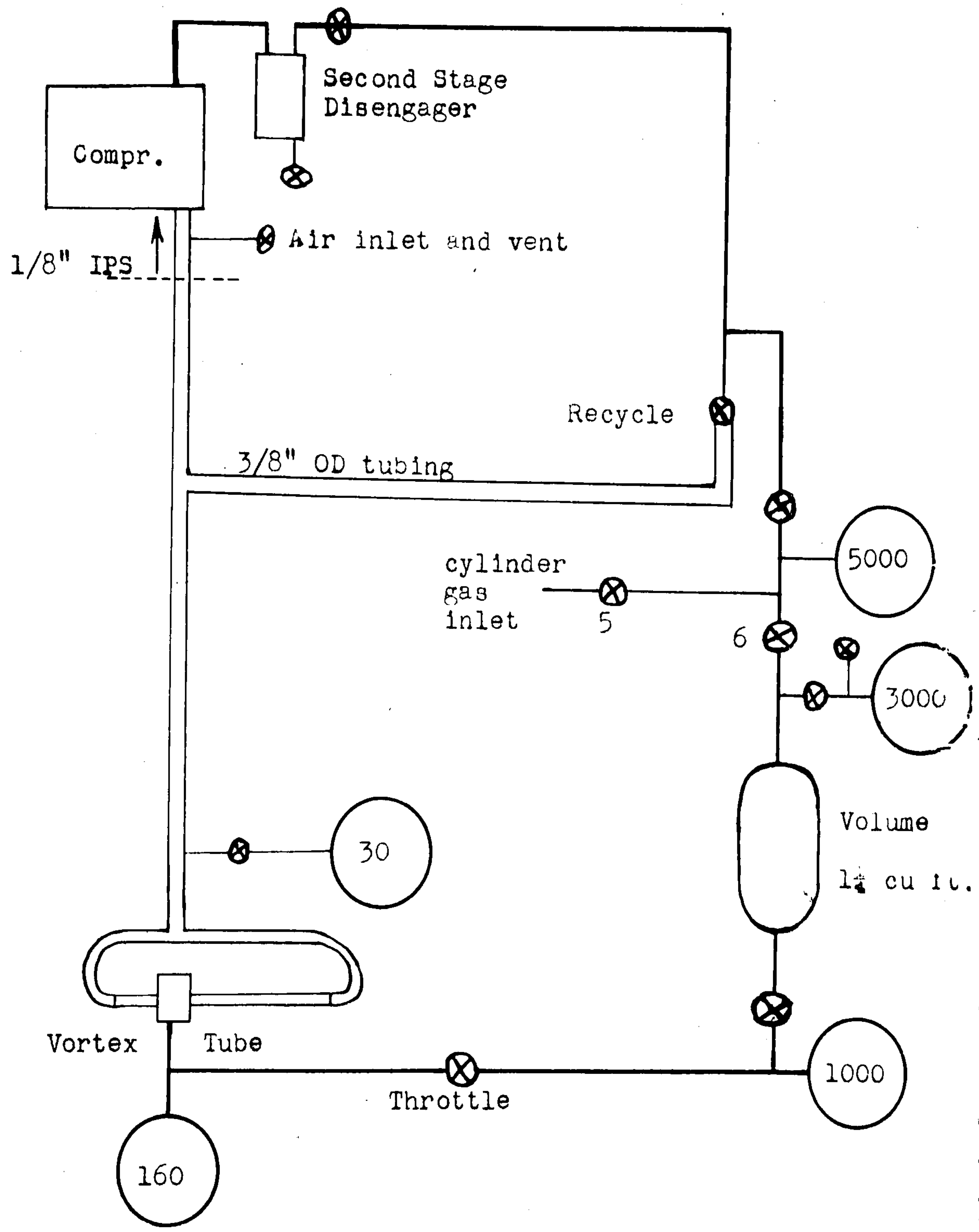
Valve-Setting	T_c °C	T_h °C	T_p °C	T_r °C	μ	P nom. psig	L_c	L_h	L_p	Notes	
							meter readings				
3/4	-2.7	26.3	20.0	25.1	.217	58.8					
3/4	-3.5	26.5	19.9	25.1	.22 .22		42.5	47.0	46.7	Special	Analysis
1-1/8	-11.5	35.0	19.8		.326		39.7	46.0	43.0	"	"
1-3/8	-14.4	42.3	19.0		.411		37.5	43.0	42.0	"	"
7/8	-7.2	28.2	19.5		.246		35.7	40.0	39.7	"	"

RUNS 70, 71

DATA TABLE II

COMPOSITION: 74.6% A, 25.4% H_2 MW: 30.31

Valve Setting	T ^{o}C	P PSIA	$\frac{S_{air}\ scfm}{S_{mix}\ cfm}$	$\mu S\rho$	ρ	η	D in.	Re	f	L in.	ΔP	P_{corr} PSIA
	21.5	14.7		.311	.074	.0186	.311	20,400	.0255	12	.137	14.8
3/4 (avgd.)	26.4	14.8		.255	.0729	.0189	.311	16,400	.027	25	.137	15.0
	-3.1	14.7	4.3 / 4.2	.056	.0808	.0174	.311			14	negl.	14.8
	21.5	73.5		.311	.39	.0188	.180	34,600	.0225	50	1.49	72.0
1-1/8	35.0	14.8										15.0
	-11.5	14.8	4.28 / 4.19									14.8
	21.4	73.5										72.0
1-3/8	42.3	14.8										14.9
	-14.4	14.8	4.14 / 4.05									14.8
	20.6	73.5		.2997	.3915						1.38	72.1
7/8	28.2	14.8										15.0
	-7.2	14.8	4.3 / 4.2									14.8
	21.1	73.5										72.0



All copper tubing ¼" OD

unless otherwise noted.

All pressures are PSIG

FLOW DIAGRAM

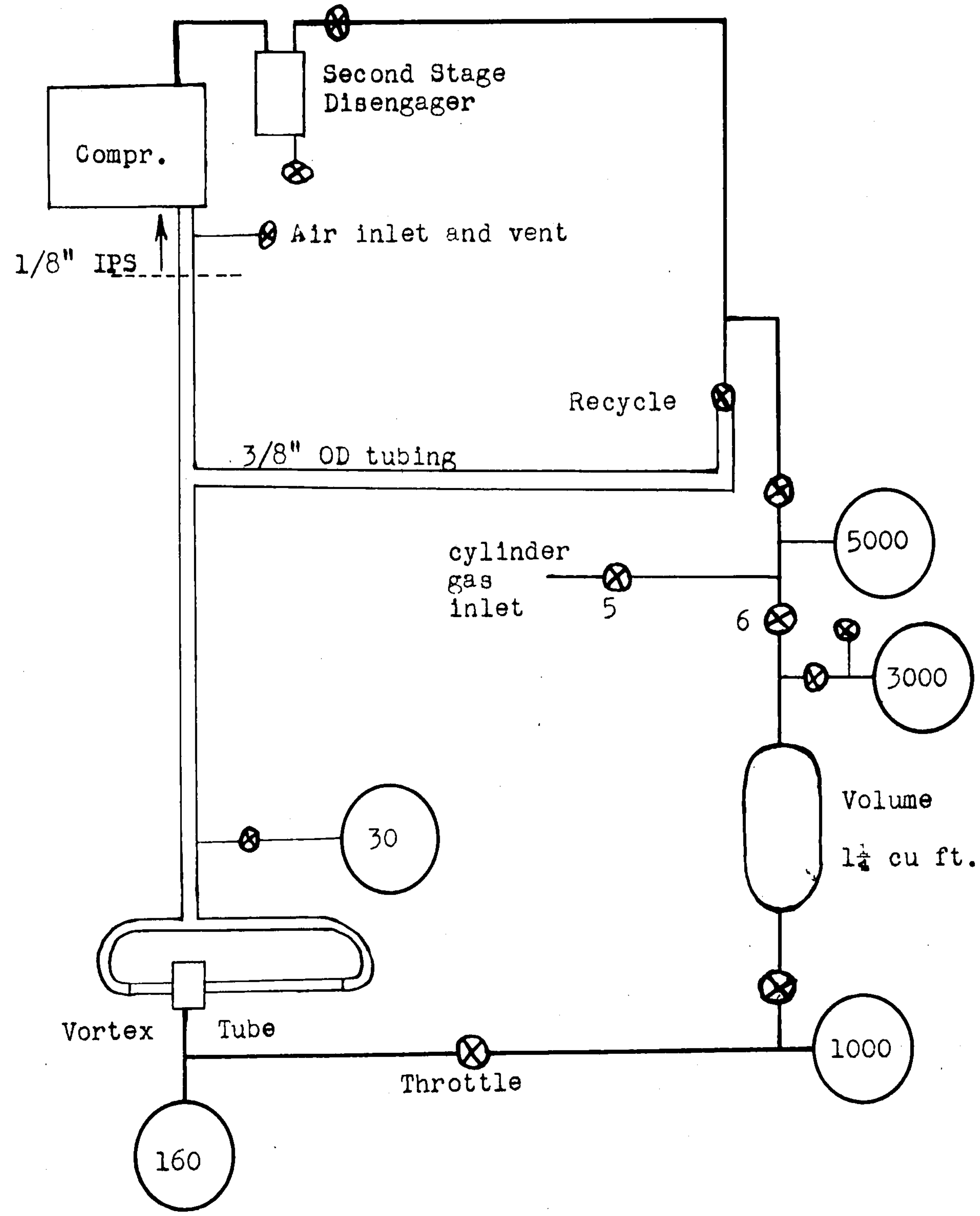
Figure 1

RUNS 70, 71

DATA TABLE II

COMPOSITION: 74.6% A, 25.4% H_2 MW: 30.31

Valve Setting	T °C	P PSIA	$\frac{S_{air}\ scfm}{S_{mix}\ cfm}$	$\mu S \rho$	ρ	η	D in.	Re	f	L in.	ΔP	P_{corr} PSIA
	21.5	14.7		.311	.074	.0186	.311	20,400	.0255	12	.137	14.8
3/4	26.4	14.8		.255	.0729	.0189	.311	16,400	.027	25	.137	15.0
(avgd.)	-3.1	14.7	4.3	.056	.0808	.0174	.311			14	negl.	14.8
	21.5	73.5	4.2	.311	.39	.0188	.180	34,600	.0225	50	1.49	72.0
1-1/8	35.0	14.8										15.0
	-11.5	14.8	4.28									14.8
	21.4	73.5	4.19									72.0
1-3/8	42.3	14.8										14.9
	-14.4	14.8	4.14									14.8
	20.6	73.5	4.05	.2997	.3915						1.38	72.1
7/8	28.2	14.8										15.0
	-7.2	14.8	4.3									14.8
	21.1	73.5	4.2									72.0



All copper tubing ¼" OD
unless otherwise noted.
All pressures are PSIG

FLOW DIAGRAM

Figure 1

MISSING

PAGES

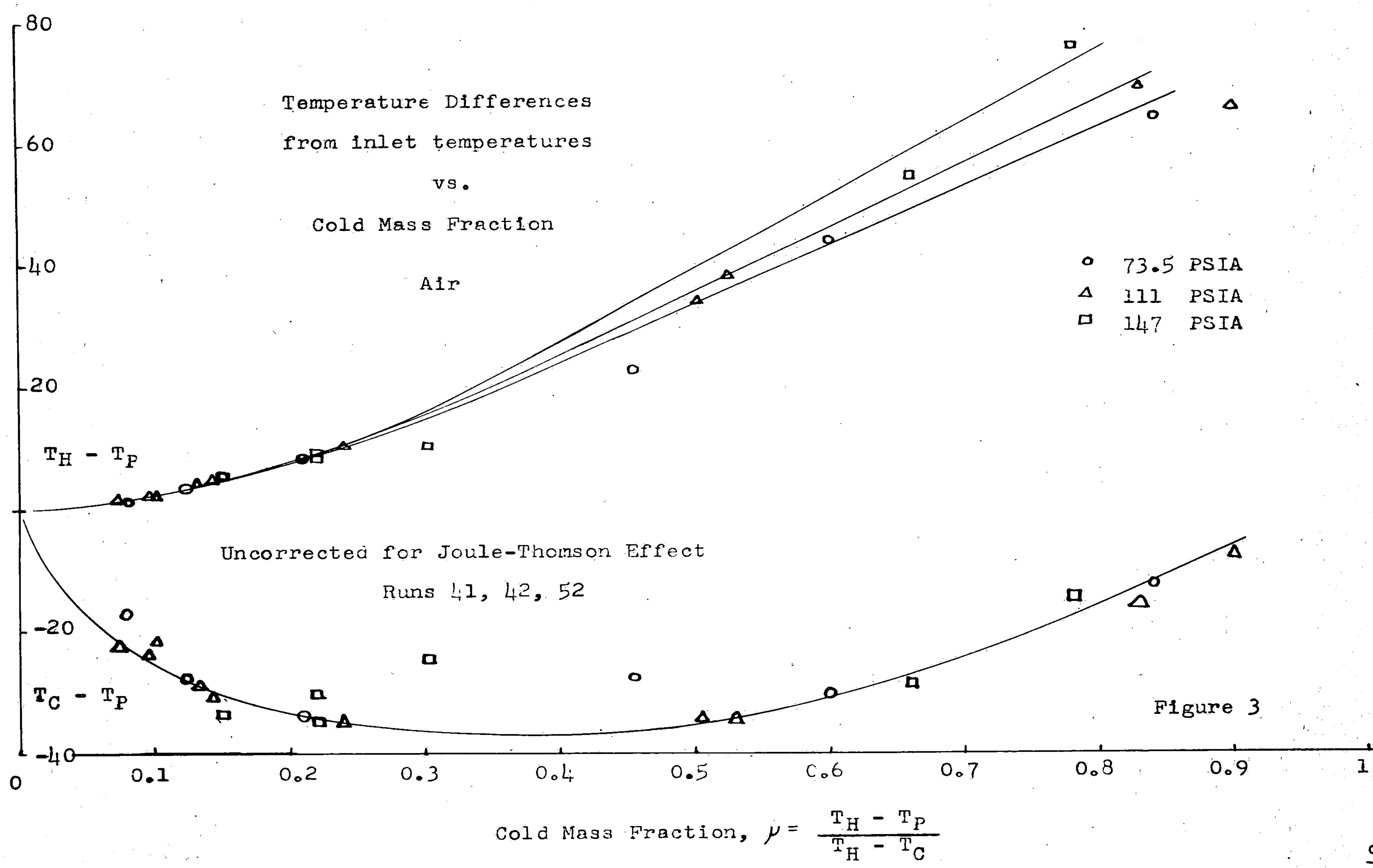
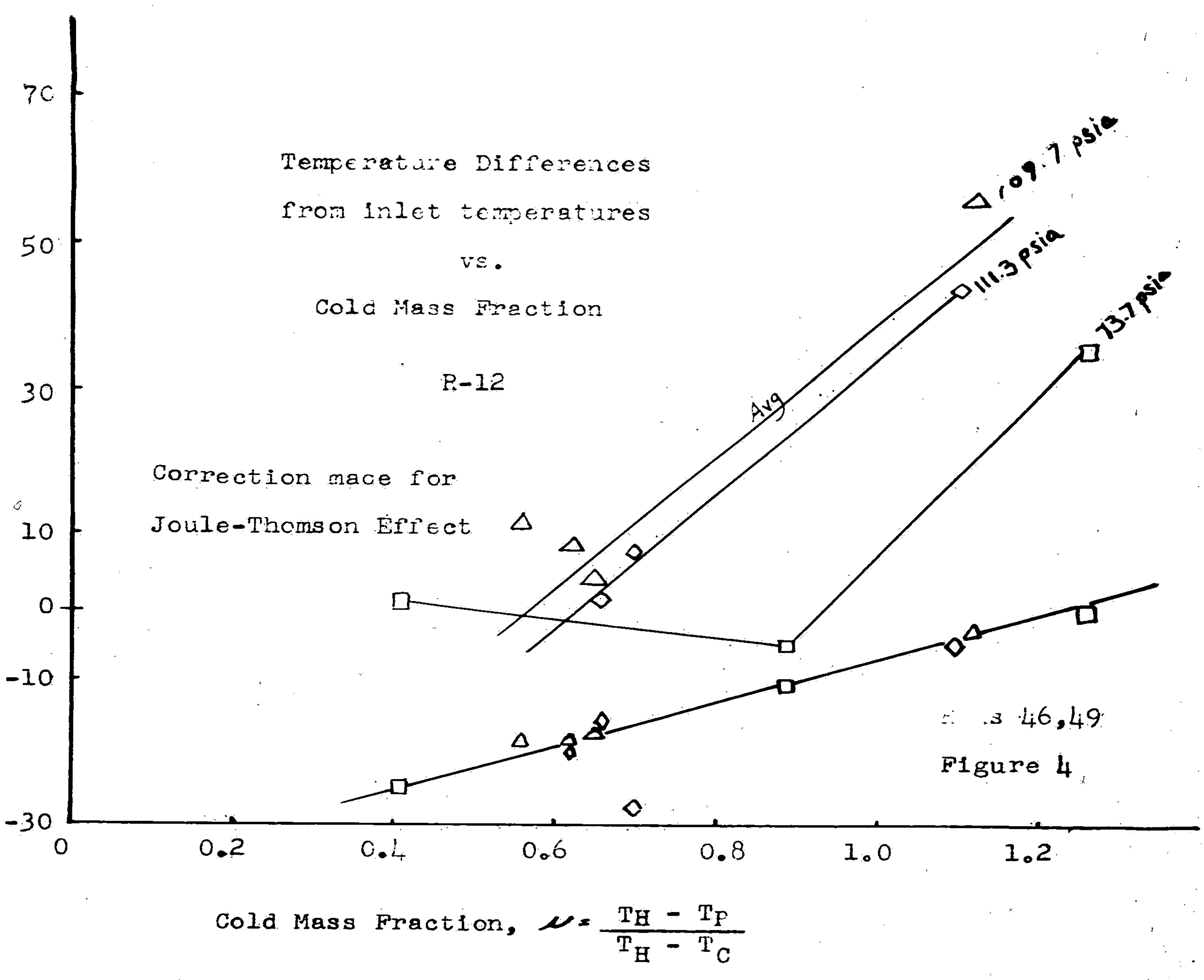
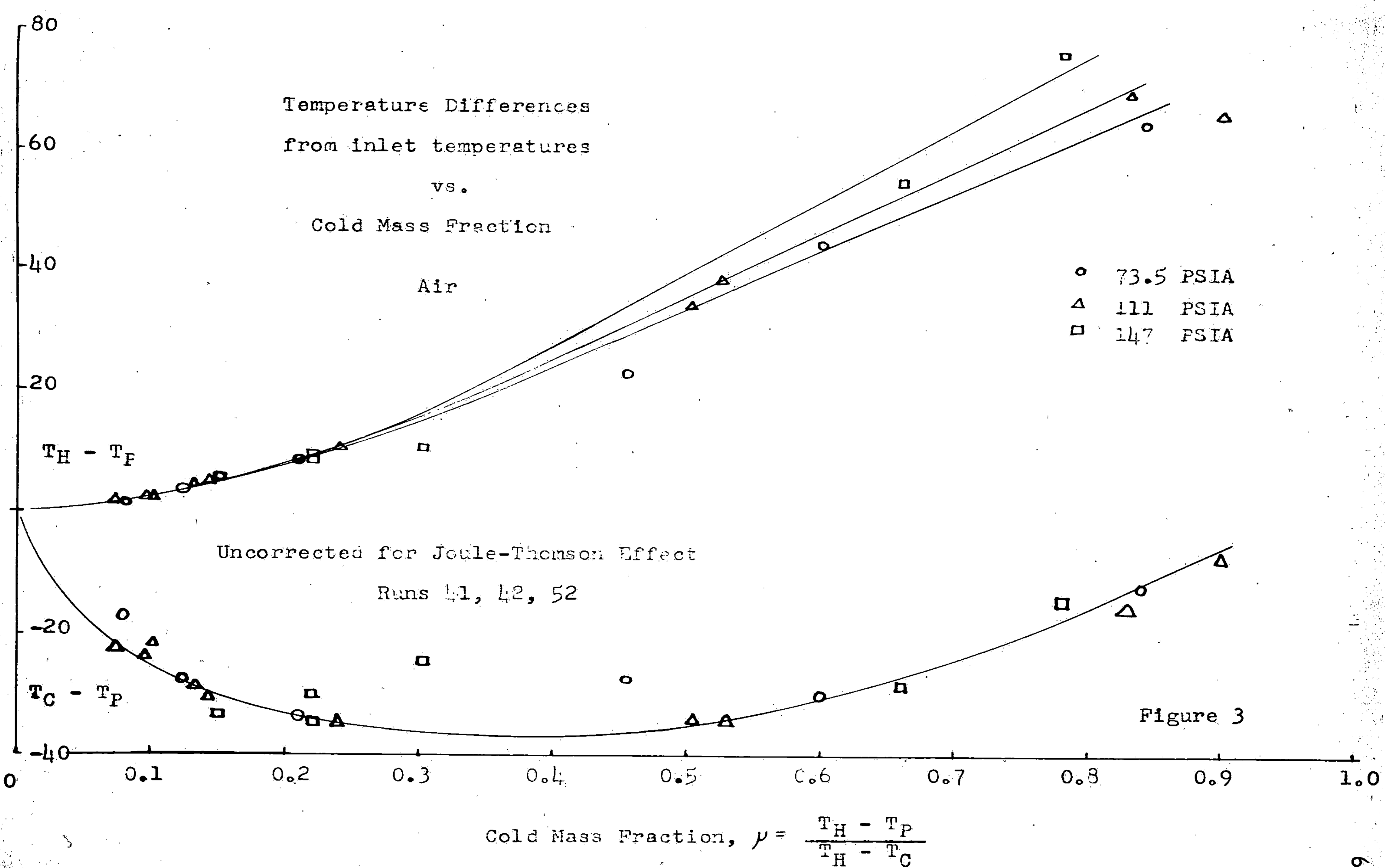

Temperature Differences
from inlet temperatures
vs.
Cold Mass Fraction
Air
○ 73.5 PSIA
△ 111 PSIA
□ 147 PSIA
$T_H - T_P$
Uncorrected for Joule-Thomson Effect
Runs 41, 42, 52
$T_C - T_P$
80
60
40
20
-20
-40
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Cold Mass Fraction, $\mu = \frac{T_H - T_P}{T_H - T_C}$

Figure 3



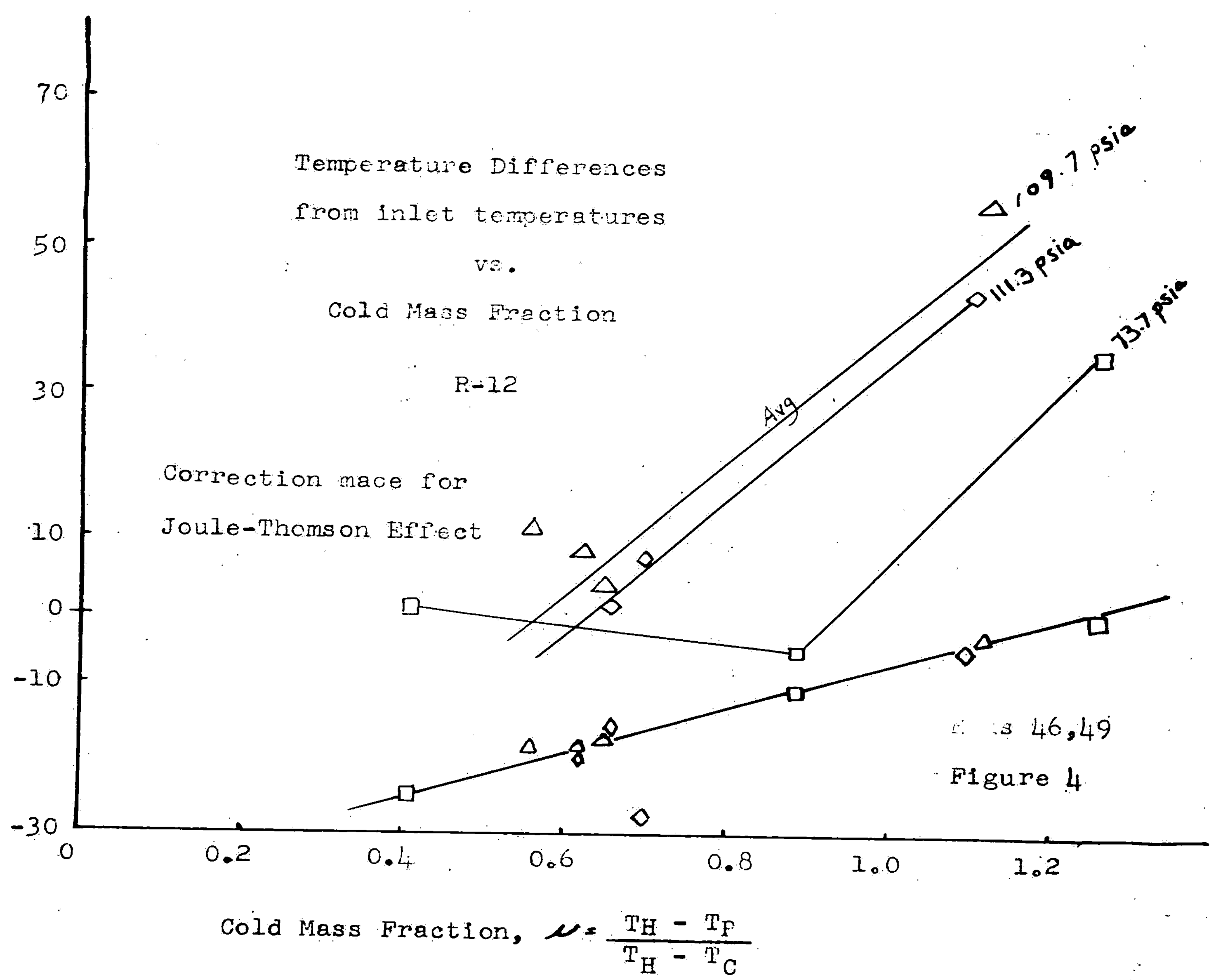
Temperature Differences
from inlet temperatures
vs.
Cold Mass Fraction
R-12
Correction made for
Joule-Thomson Effect
109.7 psia
111.3 psia
73.7 psia
Avg
70
50
30
10
0
-10
-30
0
0.2
0.4
0.6
0.8
1.0
1.2
Cold Mass Fraction, $\mu = \frac{T_H - T_P}{T_H - T_C}$

Figure 4



Temperature Differences
from inlet temperatures
vs.
Cold Mass Fraction
Air
73.5 PSIA
111 PSIA
147 PSIA
TH - TP
TC - TP
Uncorrected for Joule-Thomson Effect
Runs 41, 42, 52
80
60
40
20
-20
-40
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Cold Mass Fraction, μ = (TH - TP)/(TH - TC)

Figure 3


Temperature Differences
from inlet temperatures
vs.
Cold Mass Fraction
R-12
Correction mace for
Joule-Thomson Effect
109.7 psia
111.3 psia
73.7 psia
Avg
46,49
70
50
30
10
0
-10
-30
0
0.2
0.4
0.6
0.8
1.0
1.2
Cold Mass Fraction, μ = TH - TF / TH - TC
Figure 4

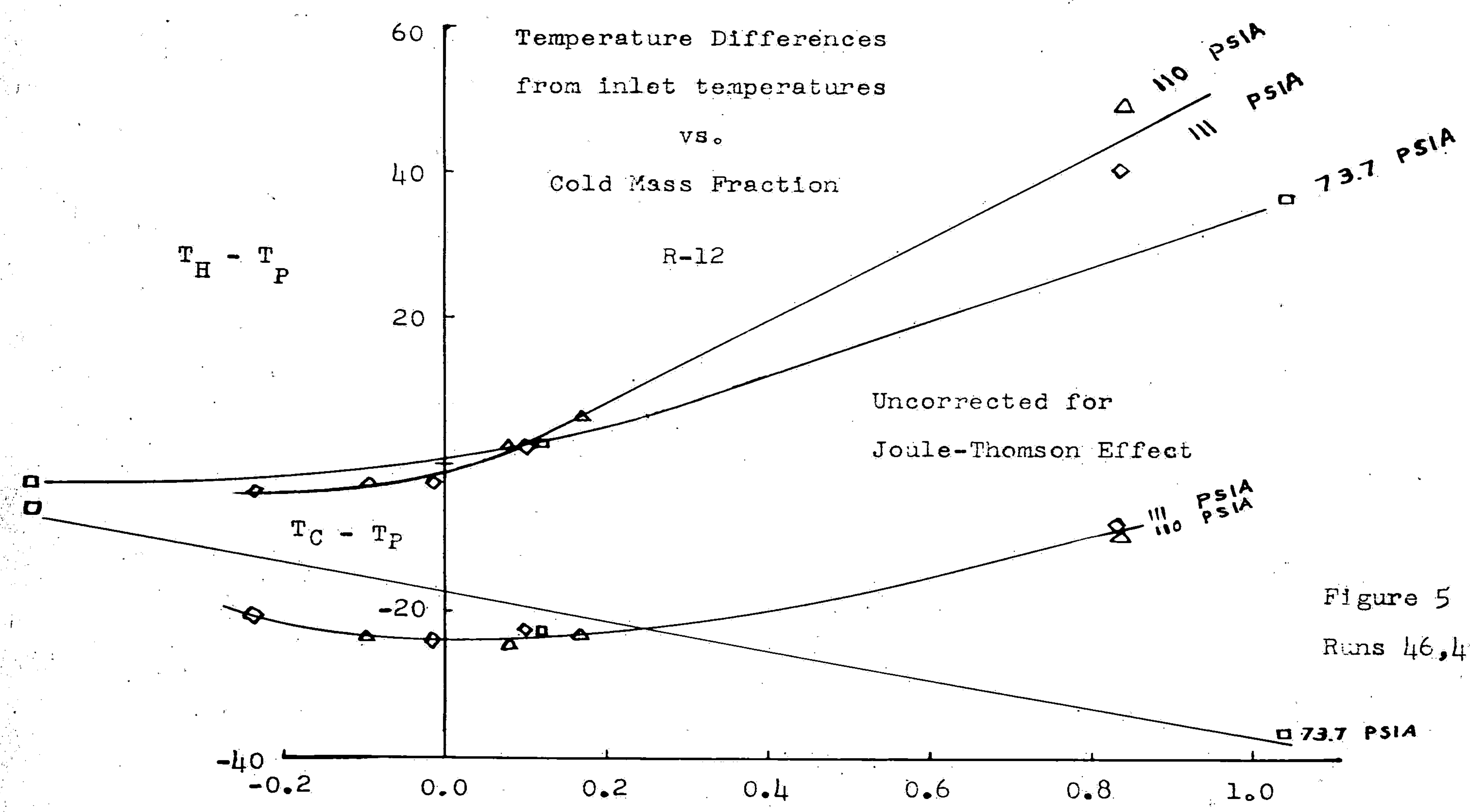


Figure 5
Runs 46,49

Cold Mass Fraction, $\mu = \dfrac{T_H - T_P}{T_H - T_C}$

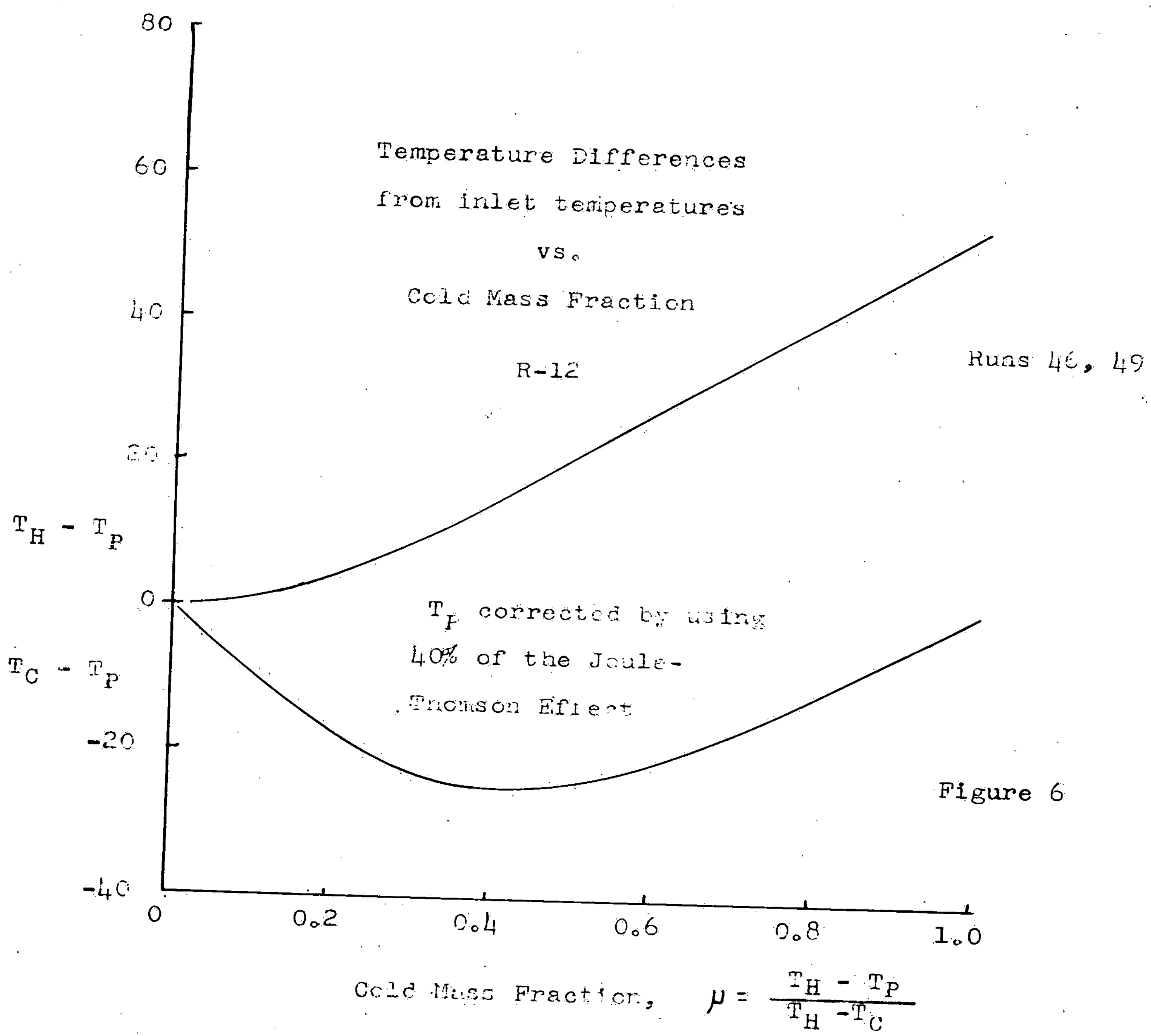

Temperature Differences
from inlet temperatures
vs.
Cold Mass Fraction
R-12
Runs 46, 49
$T_H - T_P$
$T_C - T_P$
T_P corrected by using
40% of the Joule-
Thomson Effect
80
60
40
20
0
-20
-40
0
0.2
0.4
0.6
0.8
1.0
Cold Mass Fraction, $\mu = \frac{T_H - T_P}{T_H - T_C}$

Figure 6

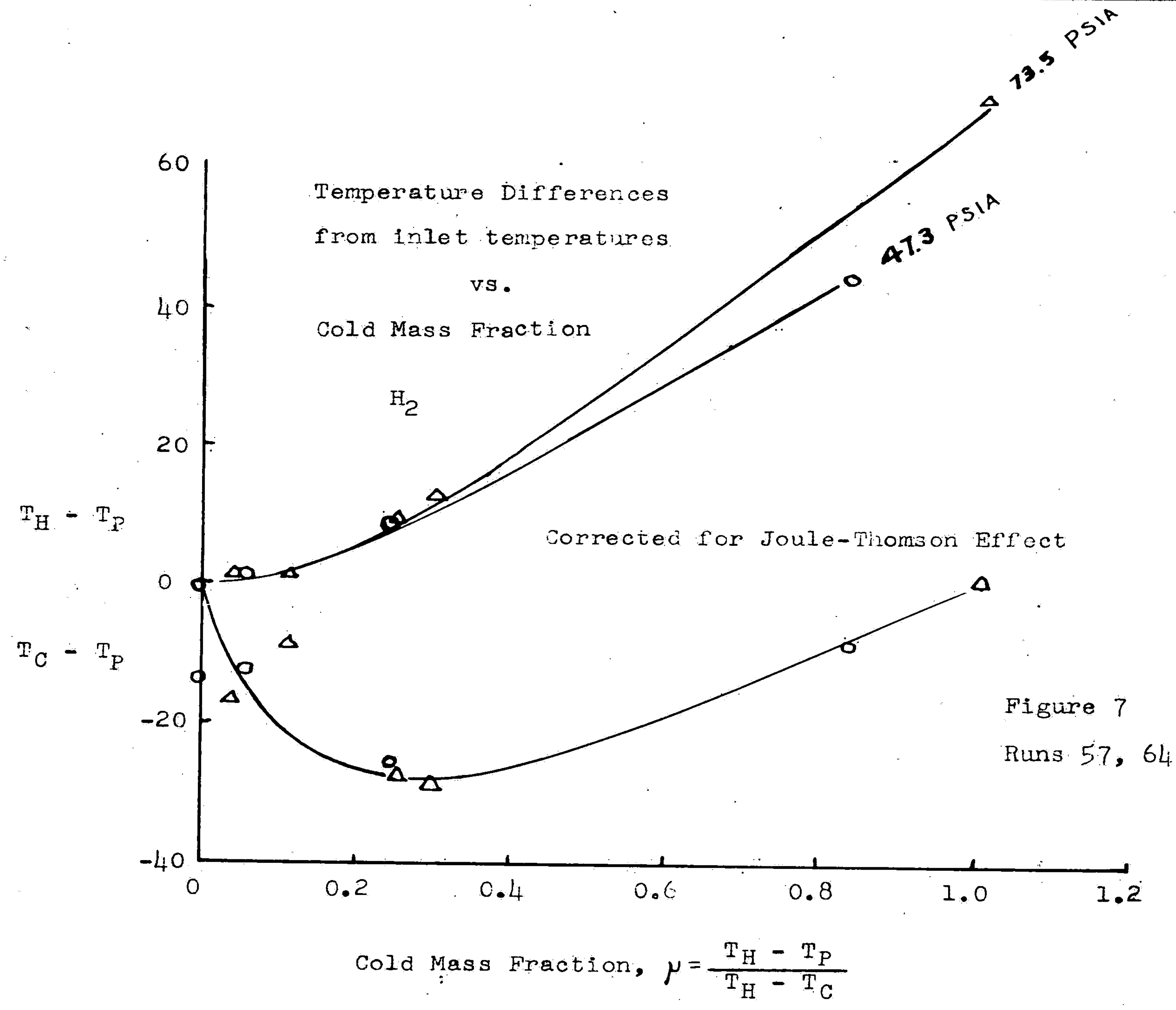


Figure 7

Runs 57, 64

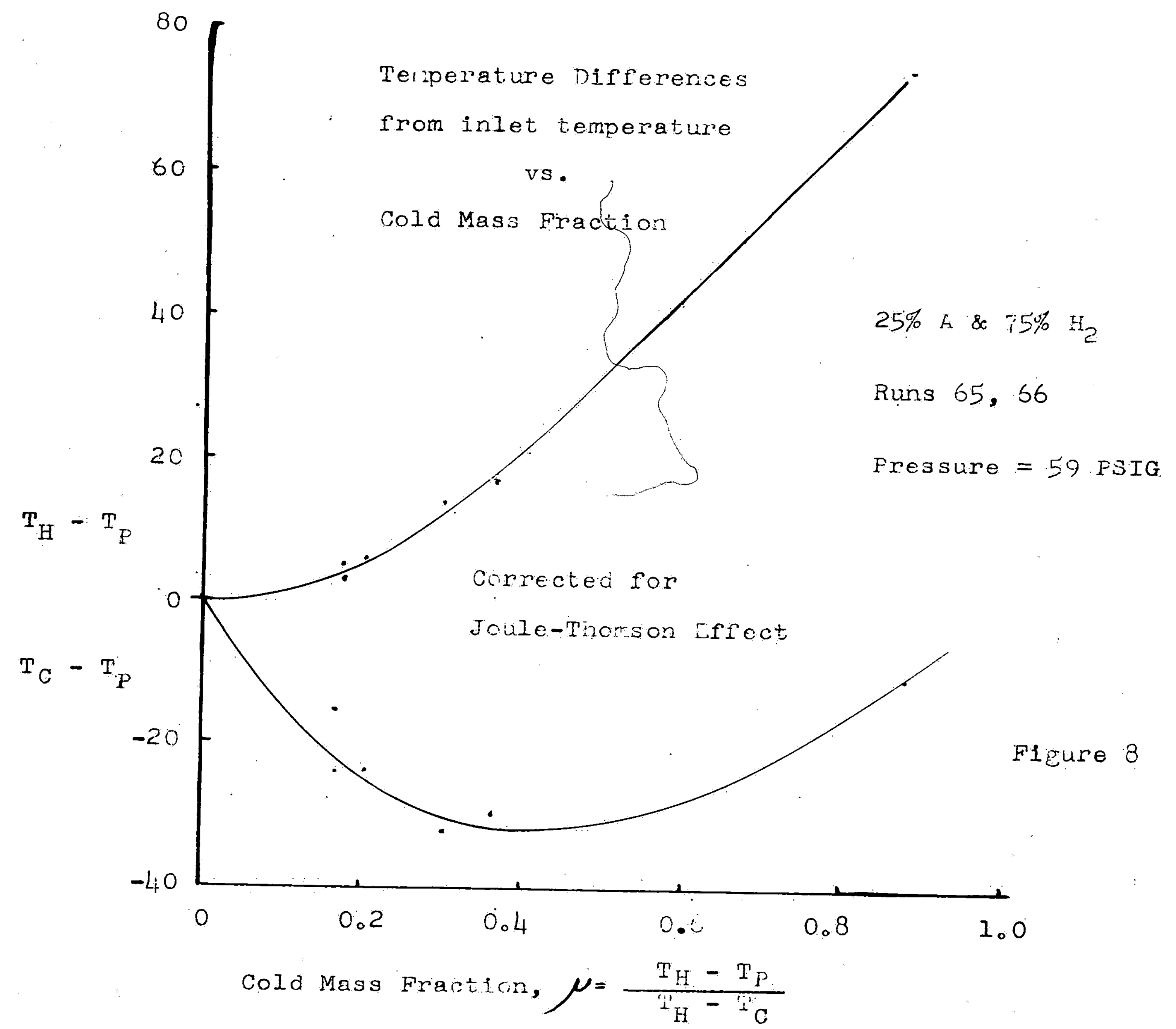

Temperature Differences
from inlet temperature
vs.
Cold Mass Fraction
25% A & 75% H_2
Runs 65, 66
Pressure = 59 PSIG
Corrected for
Joule-Thomson Effect
$T_H - T_P$
$T_C - T_P$
80
60
40
20
0
-20
-40
0
0.2
0.4
0.6
0.8
1.0
Cold Mass Fraction, $\mu = \frac{T_H - T_P}{T_H - T_C}$

Figure 8

Temperature Differences

from inlet temperatures

vs.

Cold Mass Fraction

75% A & 25% H_2

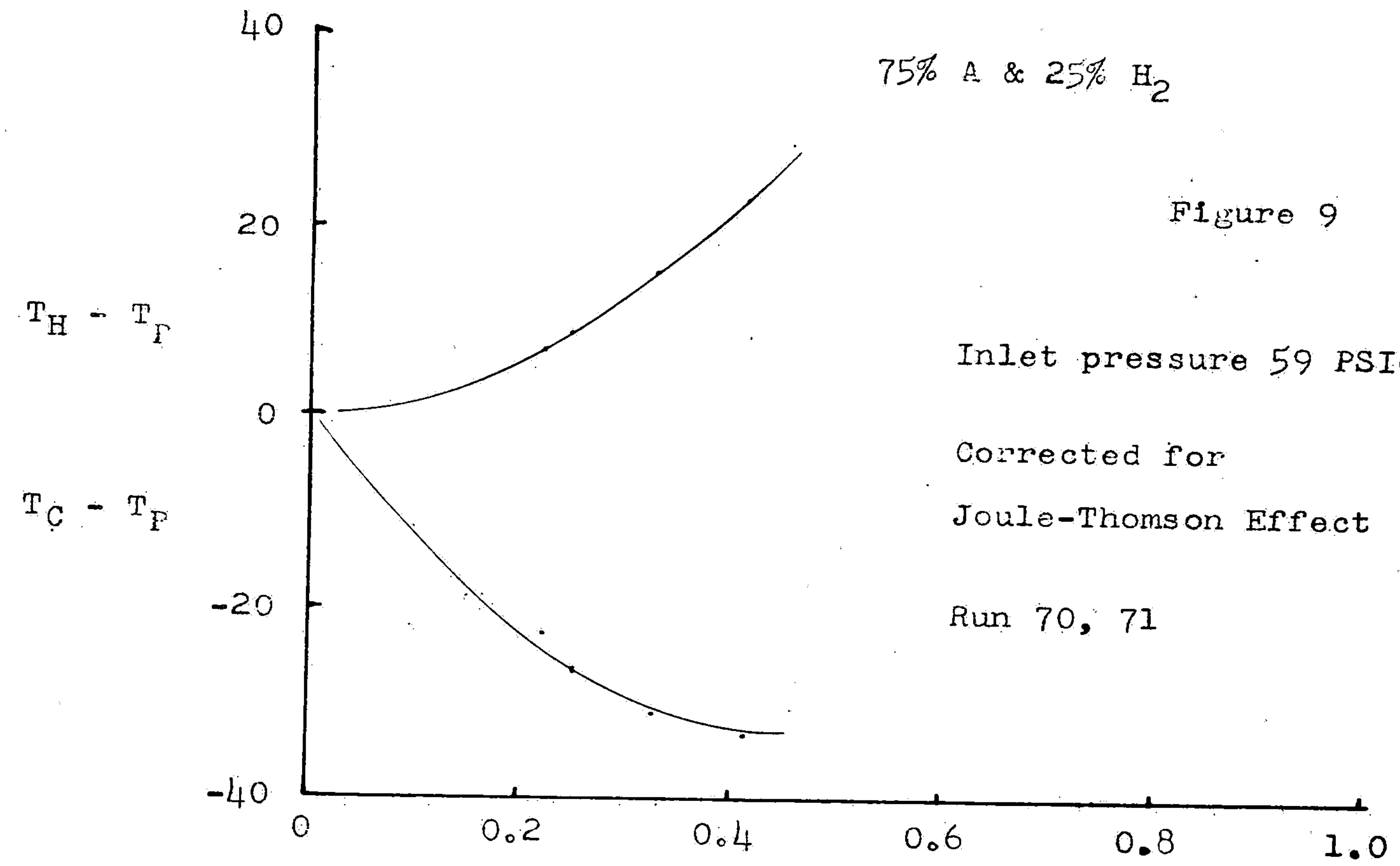
Figure 9

Inlet pressure 59 PSIG

Corrected for

Joule-Thomson Effect

Run 70, 71



Cold Mass Fraction, $\mu = \frac{T_H - T_P}{T_H - T_C}$

Temperature Differences

from inlet temperatures

vs.

Cold Mass Fraction

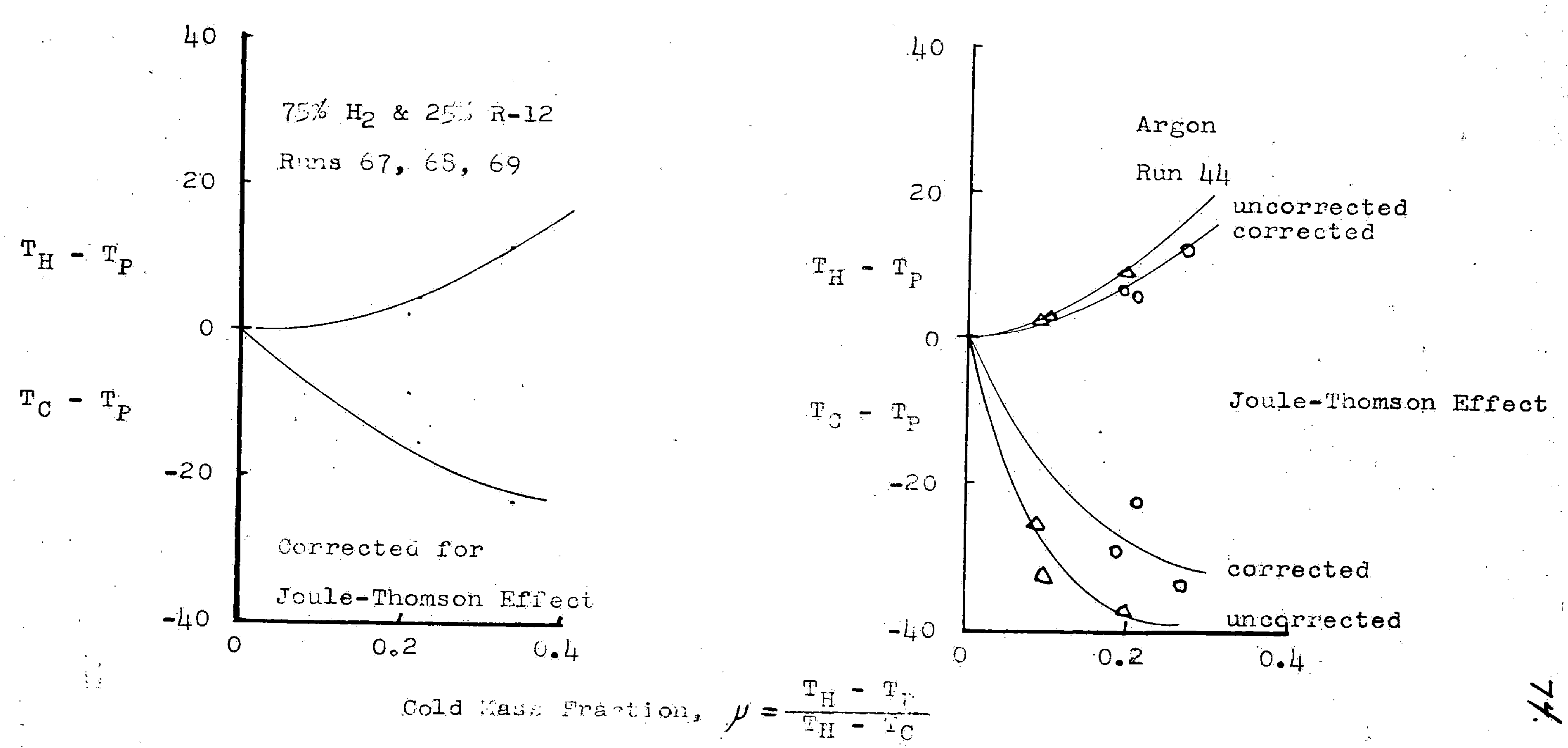
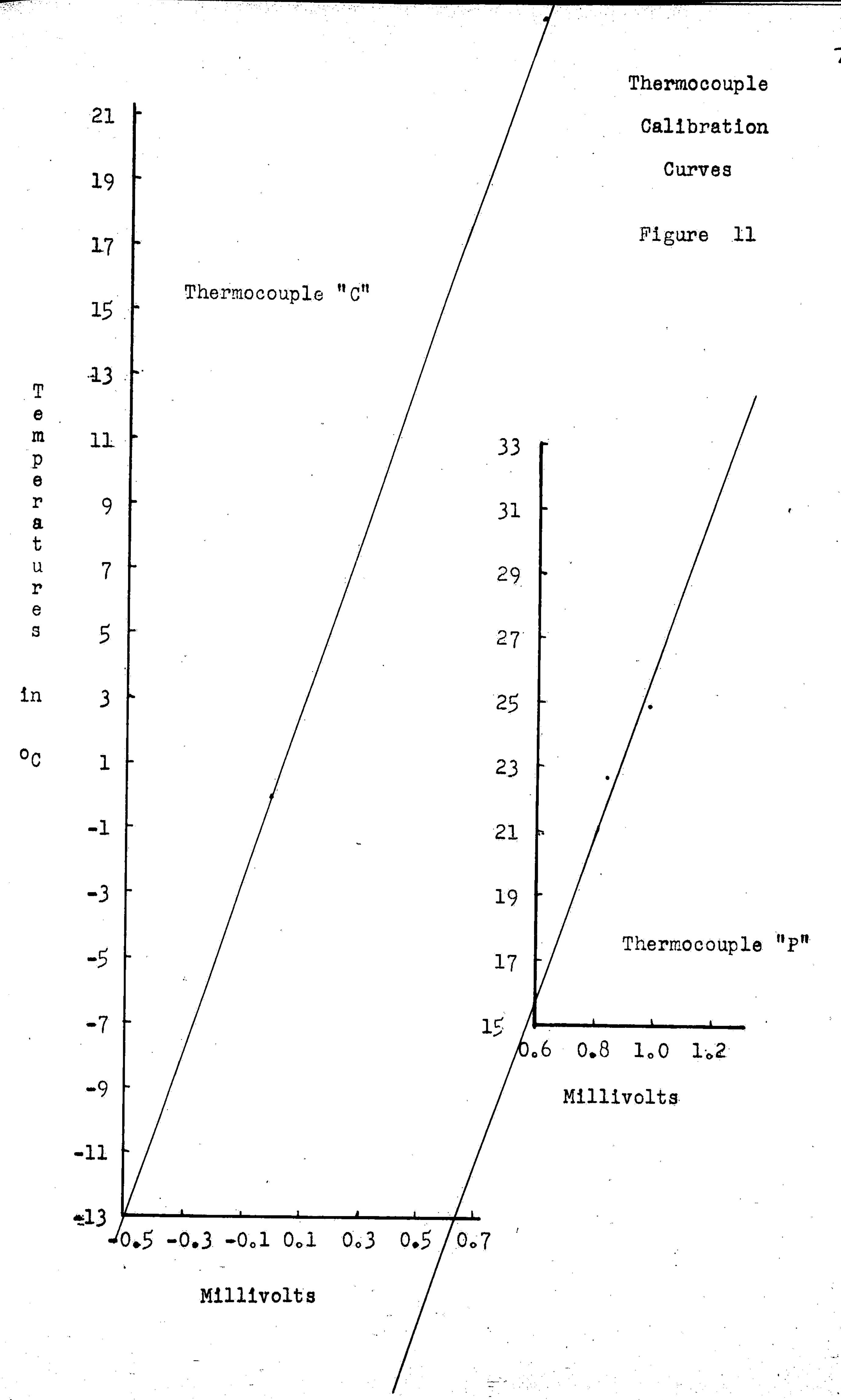


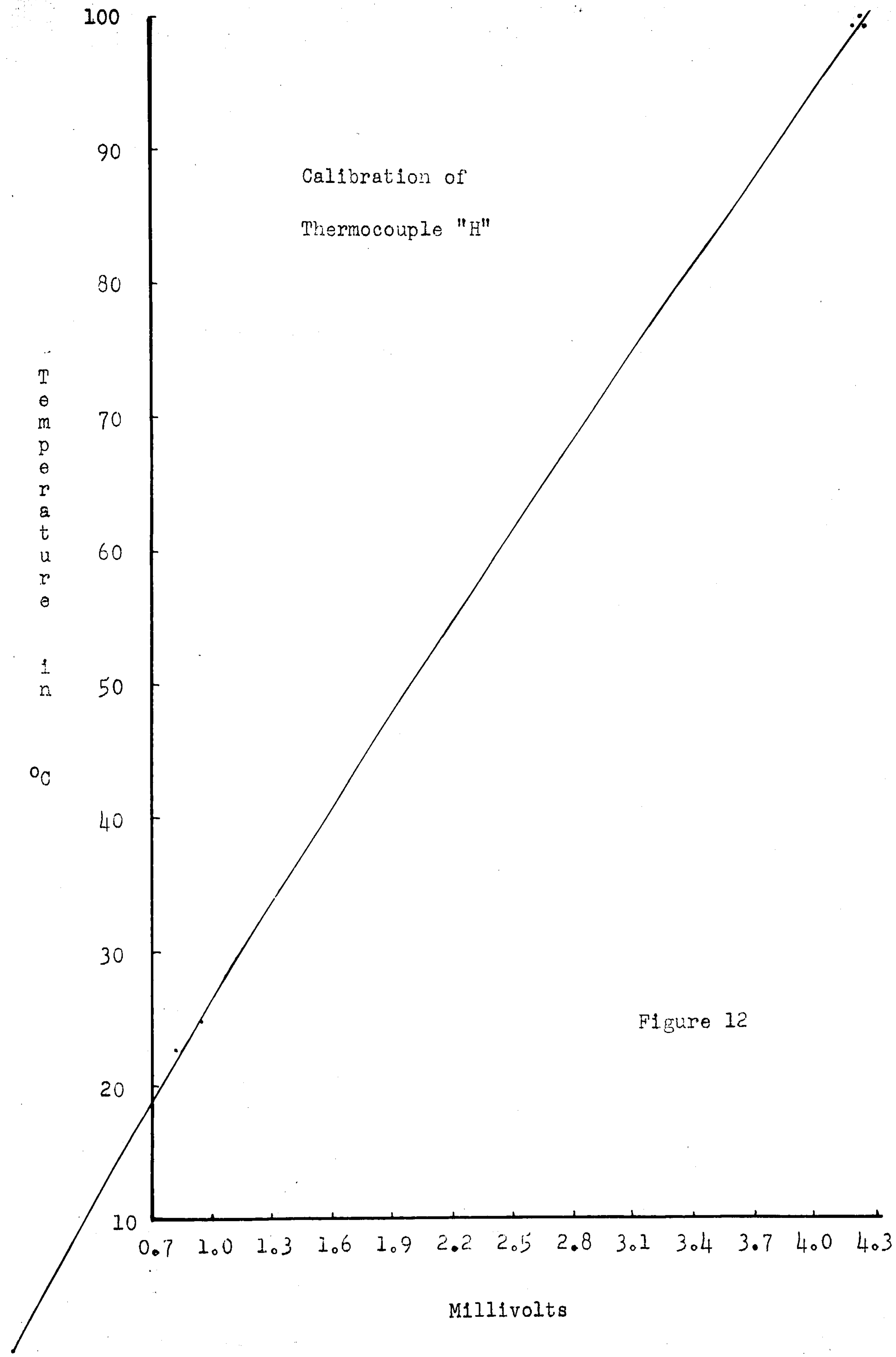
Figure 10

74

Thermocouple Calibration Curves

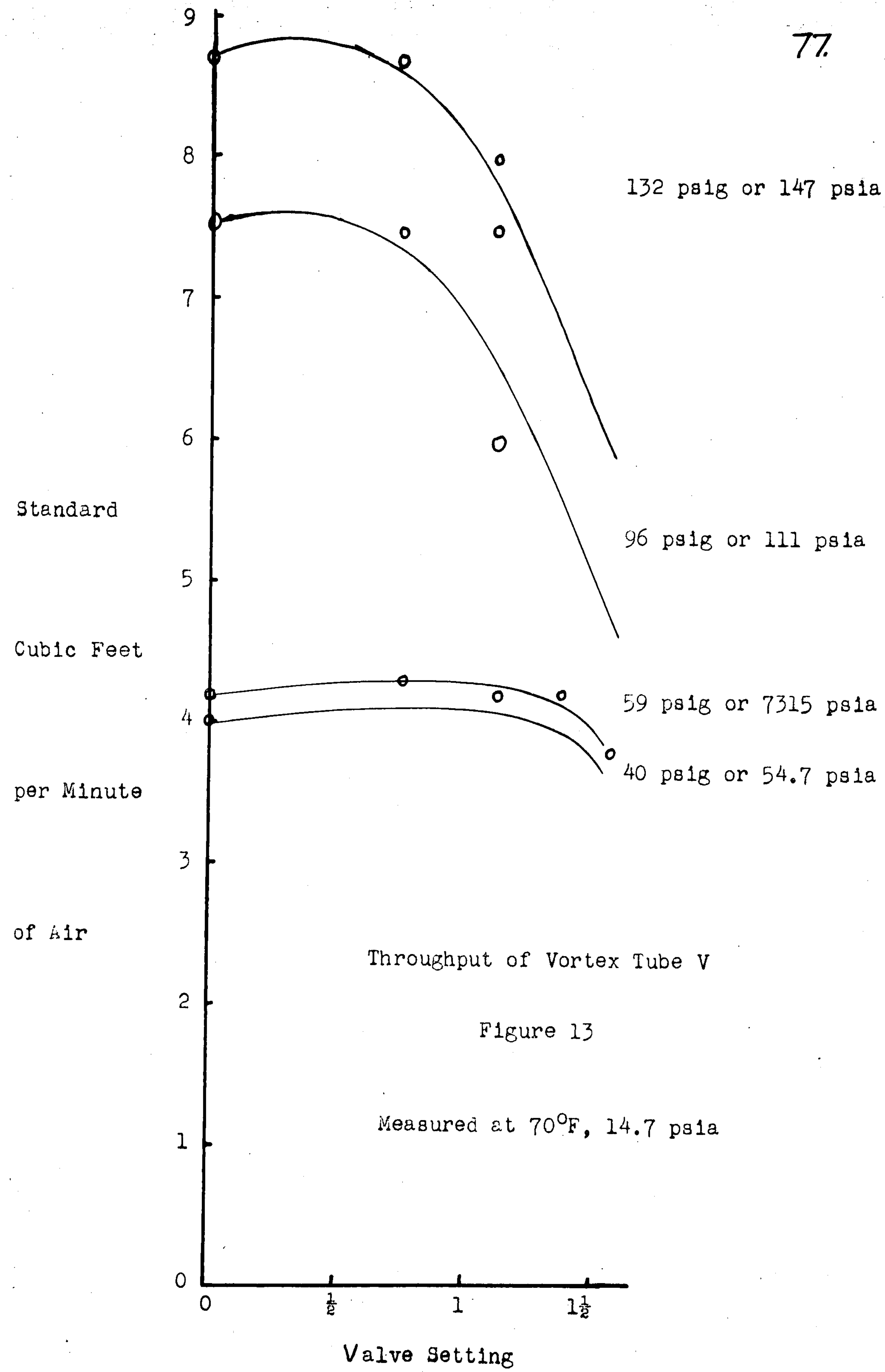
Figure 11





100
90
80
70
60
50
40
30
20
10
Calibration of
Thermocouple "H"
Temperature in °C
0.7 1.0 1.3 1.6 1.9 2.2 2.5 2.8 3.1 3.4 3.7 4.0 4.3
Millivolts

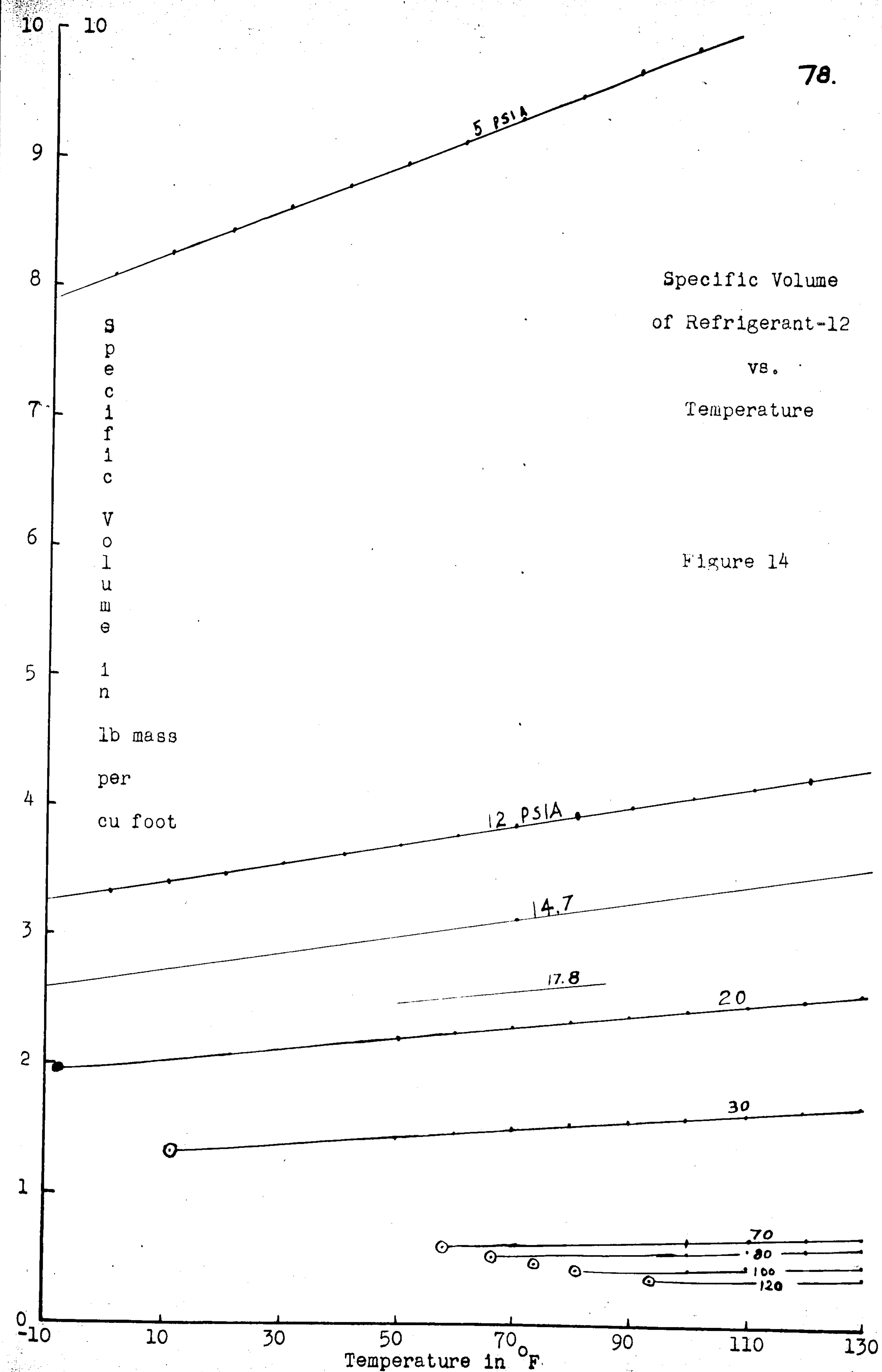
Figure 12



Throughput of Vortex Tube V

Figure 13

Measured at 70°F, 14.7 psia



Specific Volume of Refrigerant-12 vs. Temperature

Figure 14

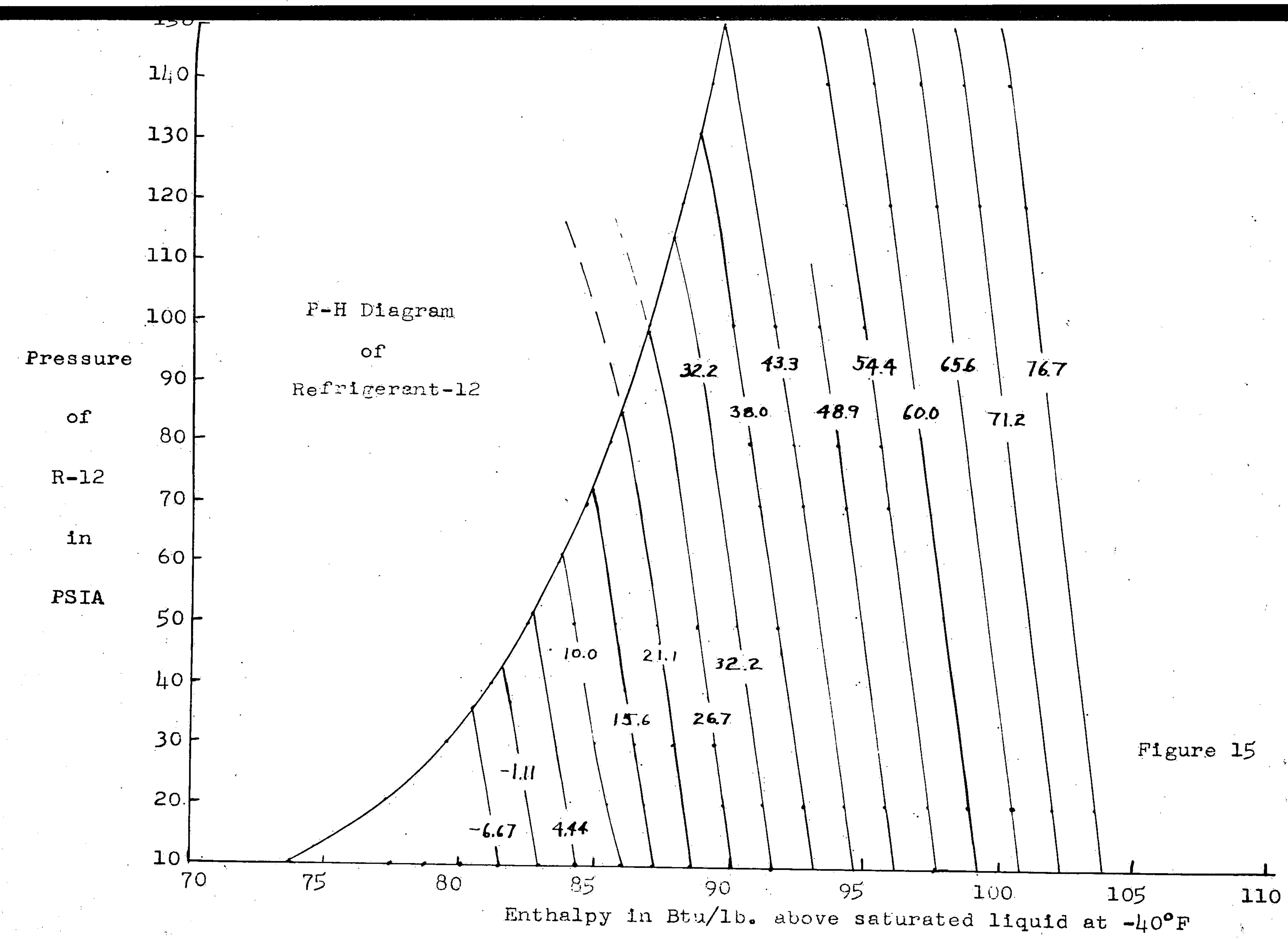

P-H Diagram
of
Refrigerant-12
Pressure
of
R-12
in
PSIA
10
20
30
40
50
60
70
80
90
100
110
120
130
140
70
75
80
85
90
95
100
105
110
Enthalpy in Btu/lb. above saturated liquid at -40°F
-6.67
-1.11
4.44
10.0
15.6
21.1
26.7
32.2
32.2
38.0
43.3
48.9
54.4
60.0
65.6
71.2
76.7

Figure 15

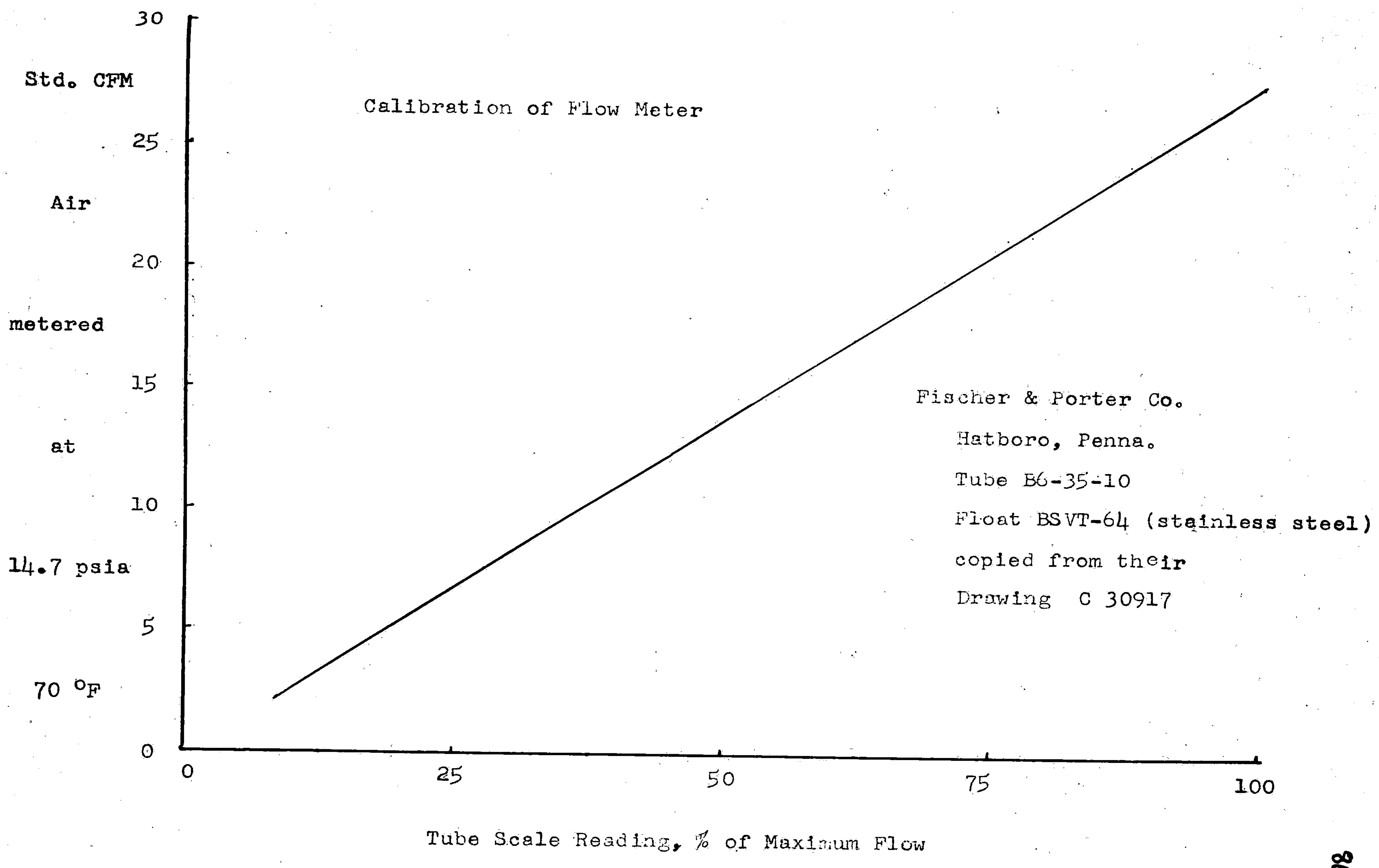

Std. CFM
Air
metered
at
14.7 psia
70 °F
30
25
20
15
10
5
0
Calibration of Flow Meter
Fischer & Porter Co.
Hatboro, Penna.
Tube B6-35-10
Float BSVT-64 (stainless steel)
copied from their
Drawing C 30917
0
25
50
75
100
Tube Scale Reading, % of Maximum Flow

Figure 16

THERMOCOUPLE CALIBRATION

Because the "C" and "P" couples broke during experimentation and repair work was done on the wiring, it was necessary to combine the following data to obtain Figures 11 and 12.

All of these were taken with the "Z" couple in an ice-water bath.

Couple	mv	°C	mv	°C	mv	°C
C	0.94	24.8	0.00	0	4.26	99.3
H	0.95	24.8	0.00	0	4.20	99.3
P	0.98	24.9	0.00	0	4.14	99.3
C	0.71	24.2	0.00	0		
H	0.83	22.7	0.00	0	4.27	99.3
P	0.84	22.7	0.00	0	4.17	99.3
H					4.24	100.0
P					4.27	100.0

The limits of error appear to be ± 0.5°C for H, ± 0.7°C for P and, very little for C.

PRESSURE GAUGES

Only three gauges were used in operation, the Dura 0-160 psig, the Clapp 0-30 psig and the Heise 0-3000 psig. It was not necessary to apply a correction to any of them. The first two were tested over their range with a dead weight tester and found to be very close to the indicated values. The Heise gauge was calibrated at the factory and was certified to be accurate to one part in a thousand. The scale was in 2 psi subdivisions, thus readable to one half psi.

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"Blows Hot and Cold"; Fortune, Dec. '46, pp. 180-183. News article. P-3

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